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DOE FUNDAMENTALS HANDBOOK

ELECTRICAL SCIENCE

Volume 1 of 4



**U.S. Department of Energy
Washington, D.C. 20585**

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ABSTRACT

The *Electrical Science Fundamentals Handbook* was developed to assist nuclear facility operating contractors provide operators, maintenance personnel, and the technical staff with the necessary fundamentals training to ensure a basic understanding of electrical theory, terminology, and application. The handbook includes information on alternating current (AC) and direct current (DC) theory, circuits, motors, and generators; AC power and reactive components; batteries; AC and DC voltage regulators; transformers; and electrical test instruments and measuring devices. This information will provide personnel with a foundation for understanding the basic operation of various types of DOE nuclear facility electrical equipment.

Key Words: Training Material, Magnetism, DC Theory, DC Circuits, Batteries, DC Generators, DC Motors, AC Theory, AC Power, AC Generators, Voltage Regulators, AC Motors, Transformers, Test Instruments, Electrical Distribution

FOREWORD

The *Department of Energy (DOE) Fundamentals Handbooks* consist of ten academic subjects, which include Mathematics; Classical Physics; Thermodynamics, Heat Transfer, and Fluid Flow; Instrumentation and Control; Electrical Science; Material Science; Mechanical Science; Chemistry; Engineering Symbology, Prints, and Drawings; and Nuclear Physics and Reactor Theory. The handbooks are provided as an aid to DOE nuclear facility contractors.

These handbooks were first published as Reactor Operator Fundamentals Manuals in 1985 for use by DOE category A reactors. The subject areas, subject matter content, and level of detail of the Reactor Operator Fundamentals Manuals were determined from several sources. DOE Category A reactor training managers determined which materials should be included, and served as a primary reference in the initial development phase. Training guidelines from the commercial nuclear power industry, results of job and task analyses, and independent input from contractors and operations-oriented personnel were all considered and included to some degree in developing the text material and learning objectives.

The *DOE Fundamentals Handbooks* represent the needs of various DOE nuclear facilities' fundamental training requirements. To increase their applicability to nonreactor nuclear facilities, the Reactor Operator Fundamentals Manual learning objectives were distributed to the Nuclear Facility Training Coordination Program Steering Committee for review and comment. To update their reactor-specific content, DOE Category A reactor training managers also reviewed and commented on the content. On the basis of feedback from these sources, information that applied to two or more DOE nuclear facilities was considered generic and was included. The final draft of each of the handbooks was then reviewed by these two groups. This approach has resulted in revised modular handbooks that contain sufficient detail such that each facility may adjust the content to fit their specific needs.

Each handbook contains an abstract, a foreword, an overview, learning objectives, and text material, and is divided into modules so that content and order may be modified by individual DOE contractors to suit their specific training needs. Each subject area is supported by a separate examination bank with an answer key.

The *DOE Fundamentals Handbooks* have been prepared for the Assistant Secretary for Nuclear Energy, Office of Nuclear Safety Policy and Standards, by the DOE Training Coordination Program. This program is managed by EG&G Idaho, Inc.

OVERVIEW

The *Department of Energy Fundamentals Handbook* entitled *Electrical Science* was prepared as an information resource for personnel who are responsible for the operation of the Department's nuclear facilities. A basic understanding of electricity and electrical systems is necessary for DOE nuclear facility operators, maintenance personnel, and the technical staff to safely operate and maintain the facility and facility support systems. The information in the handbook is presented to provide a foundation for applying engineering concepts to the job. This knowledge will help personnel more fully understand the impact that their actions may have on the safe and reliable operation of facility components and systems.

The *Electrical Science* handbook consists of fifteen modules that are contained in four volumes. The following is a brief description of the information presented in each module of the handbook.

Volume 1 of 4

Module 1 - Basic Electrical Theory

This module describes basic electrical concepts and introduces electrical terminology.

Module 2 - Basic DC Theory

This module describes the basic concepts of direct current (DC) electrical circuits and discusses the associated terminology.

Volume 2 of 4

Module 3 - DC Circuits

This module introduces the rules associated with the reactive components of inductance and capacitance and how they affect DC circuits.

Module 4 - Batteries

This module introduces batteries and describes the types of cells used, circuit arrangements, and associated hazards.

Module 5 - DC Generators

This module describes the types of DC generators and their application in terms of voltage production and load characteristics.

Module 6 - DC Motors

This module describes the types of DC motors and includes discussions of speed control, applications, and load characteristics.

Volume 3 of 4

Module 7 - Basic AC Theory

This module describes the basic concepts of alternating current (AC) electrical circuits and discusses the associated terminology.

Module 8 - AC Reactive Components

This module describes inductance and capacitance and their effects on AC circuits.

Module 9 - AC Power

This module presents power calculations for single-phase and three-phase AC circuits and includes the power triangle concept.

Module 10 - AC Generators

This module describes the operating characteristics of AC generators and includes terminology, methods of voltage production, and methods of paralleling AC generation sources.

Module 11 - Voltage Regulators

This module describes the basic operation and application of voltage regulators.

Volume 4 of 4

Module 12 - AC Motors

This module explains the theory of operation of AC motors and discusses the various types of AC motors and their application.

Module 13 - Transformers

This module introduces transformer theory and includes the types of transformers, voltage/current relationships, and application.

Module 14 - Test Instruments and Measuring Devices

This module describes electrical measuring and test equipment and includes the parameters measured and the principles of operation of common instruments.

Module 15 - Electrical Distribution Systems

This module describes basic electrical distribution systems and includes characteristics of system design to ensure personnel and equipment safety.

The information contained in this handbook is by no means all encompassing. An attempt to present the entire subject of electrical science would be impractical. However, the *Electrical Science* handbook does present enough information to provide the reader with a fundamental knowledge level sufficient to understand the advanced theoretical concepts presented in other subject areas, and to better understand basic system and equipment operations.

**Department of Energy
Fundamentals Handbook**

**ELECTRICAL SCIENCE
Module 1
Basic Electrical Theory**

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REFERENCES

- Gussow, Milton, Schaum's Outline Series, Basic Electricity, McGraw-Hill.
- Academic Program for Nuclear Power Plant Personnel, Volume IV, Columbia, MD: General Physics Corporation, Library of Congress Card #A 326517, 1982.
- Sienko and Plane, Chemical Principles and Properties, 2nd Edition, McGraw-Hill.
- Academic Program for Nuclear Power Plant Personnel, Volume II, Columbia, MD: General Physics Corporation, Library of Congress Card #A 326517, 1982.
- Nasar and Unnewehr, Electromechanics and Electric Machines, John Wiley and Sons.
- Van Valkenburgh, Nooger, and Neville, Basic Electricity, Vol. 5, Hayden Book Company.
- Exide Industrial Marketing Division, The Storage Battery, Lead-Acid Type, The Electric Storage Battery Company.
- Lister, Eugene C., Electric Circuits and Machines, 5th Edition, McGraw-Hill.
- Croft, Carr, Watt, and Summers, American Electricians Handbook, 10th Edition, McGraw-Hill.
- Mason, C. Russel, The Art and Science of Protective Relaying, John Wiley and Sons.
- Mileaf, Harry, Electricity One - Seven, Revised 2nd Edition, Hayden Book Company.
- Buban and Schmitt, Understanding Electricity and Electronics, 3rd Edition, McGraw-Hill.
- Kidwell, Walter, Electrical Instruments and Measurements, McGraw-Hill.

TERMINAL OBJECTIVE

1.0 Given a simple electrical circuit, **APPLY** basic electrical theory fundamental principles to describe circuit operation.

ENABLING OBJECTIVES

1.1 **DESCRIBE** the following terms:

- a. Electrostatic force
- b. Electrostatic field
- c. Potential difference
- d. Electromotive force (EMF)
- e. Ion charge

1.2 **DEFINE** the following terms:

- a. Conductor
- b. Insulator
- c. Resistor
- d. Electron current flow
- e. Conventional current flow
- f. Direct current (DC)
- g. Alternating current (AC)
- h. Ideal source
- i. Real source

1.3 **DESCRIBE** the following electrical parameters, including the unit of measurement and the relationship to other parameters.

- a. Voltage
- b. Current
- c. Resistance
- d. Conductance
- e. Power
- f. Inductance
- g. Capacitance

1.4 Given any two of the three component values of Ohm's Law, **DETERMINE** the unknown component value.

ENABLING OBJECTIVES (Cont.)

1.5 **DESCRIBE** how the following methods produce a voltage:

- Electrochemistry
- Static electricity
- Magnetic Induction
- Piezoelectric effect
- Thermoelectricity
- Photoelectric effect
- Thermionic emission

1.6 **DEFINE** the following terms:

- Magnetic flux
- Magnetic flux density
- Weber
- Permeability
- Magnetomotive force (mmf)
- Ampere turns
- Field intensity
- Reluctance

1.7 **DESCRIBE** the following materials as they relate to permeability, including an example and an approximate relative permeability.

- Ferromagnetic materials
- Paramagnetic materials
- Diamagnetic materials

1.8 **EXPLAIN** the physical qualities of a simple magnetic circuit, including relationships of qualities and units of measurements.

1.9 Given the physical qualities of a simple magnetic circuit, **CALCULATE** the unknown values.

1.10 **DESCRIBE** the shape and components of a BH magnetization curve.

1.11 **EXPLAIN** the cause of hysteresis losses.

1.12 Given Faraday's Law of induced voltage:

- DESCRIBE** how varying parameters affect induced voltage.
- CALCULATE** voltage induced in a conductor moving through a magnetic field.

1.13 **STATE** Lenz's Law of induction.

ENABLING OBJECTIVES (Cont.)

1.14 Given a standard electrical symbol, **IDENTIFY** the component that the symbol represents.
The symbols will be for the following components:

a. Resistor	m. Fuse
b. Capacitor	n. Junction
c. Inductor	o. AC voltage source
d. Relay	p. Voltmeter
e. Contacts	q. Ammeter
f. Breaker	r. Wattmeter
g. Switch	s. Relay operated contacts
h. Transistor	t. Potential transformer
i. Rheostat	u. Current transformer
j. Diode	v. Wye (Y) connection
k. Ground connections	w. Delta (Δ) connection
l. Vacuum tube	x. Light bulb
	y. Battery

ATOM AND ITS FORCES

What is electricity? Electricity is defined as "the flow of electrons through simple materials and devices" or "that force which moves electrons." Scientists think electricity is produced by very tiny particles called electrons and protons. These particles are too small to be seen, but exist as subatomic particles in the atom. To understand how they exist, you must first understand the structure of the atom.

EO 1.1 DESCRIBE the following terms:

- a. **Electrostatic force**
- b. **Electrostatic field**
- c. **Potential difference**
- d. **Electromotive force (EMF)**
- e. **Ion charge**

The Atom

Elements are the basic building blocks of all matter. The atom is the smallest particle to which an element can be reduced while still keeping the properties of that element. An atom consists of a positively charged nucleus surrounded by negatively charged electrons, so that the atom as a whole is electrically neutral. The nucleus is composed of two kinds of subatomic particles, protons and neutrons, as shown in Figure 1. The proton carries a single unit positive charge equal in magnitude to the electron charge. The neutron is slightly heavier than the proton and is electrically neutral, as the name implies. These two particles exist in various combinations, depending upon the element involved. The electron is the fundamental negative charge (-) of electricity and revolves around the nucleus, or center, of the atom in concentric orbits, or shells.

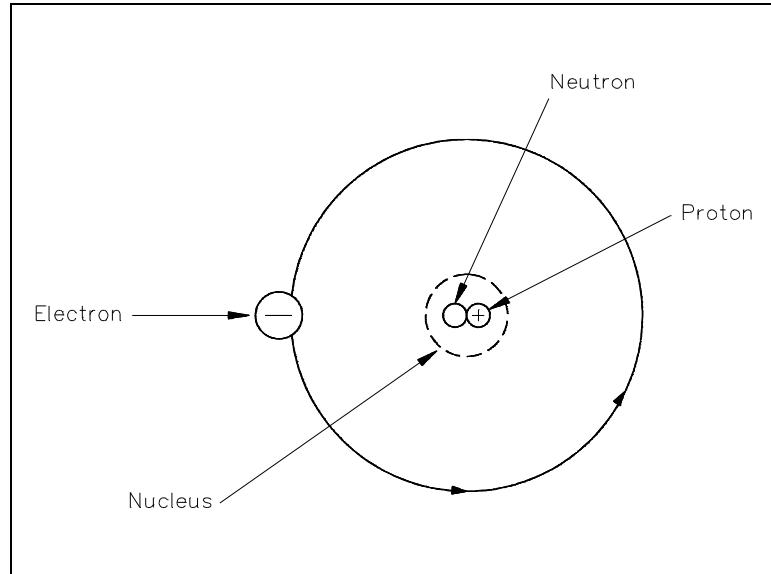


Figure 1 The Atom

The proton is the fundamental positive charge (+) of electricity and is located in the nucleus. The number of protons in the nucleus of any atom specifies the atomic number of that atom or of that element. For example, the carbon atom contains six protons in its nucleus; therefore, the atomic number for carbon is six, as shown in Figure 2.

In its natural state, an atom of any element contains an equal number of electrons and protons. The negative charge (-) of each electron is equal in magnitude to the positive charge (+) of each proton; therefore, the two opposite charges cancel, and the atom is said to be electrically neutral, or in balance.

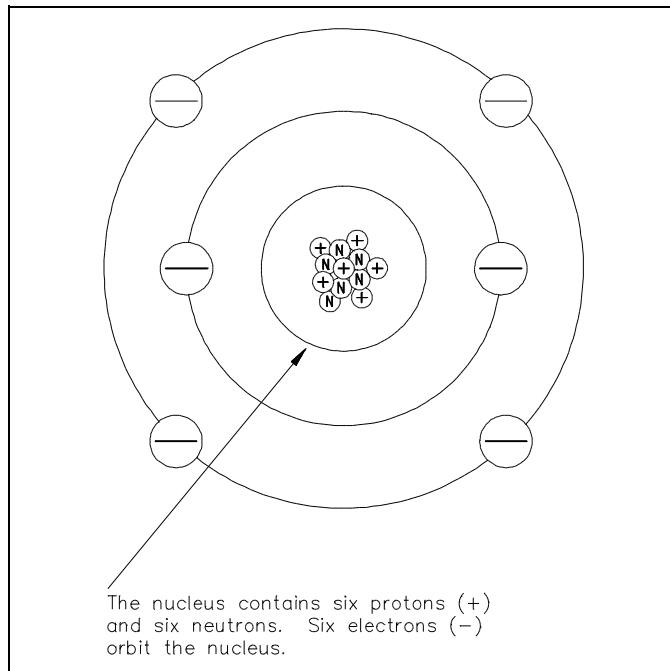


Figure 2 The Carbon Atom

One of the mysteries of the atom is that the electron and the nucleus attract each other. This attraction is called *electrostatic force*, the force that holds the electron in orbit. This force may be illustrated with lines as shown in Figure 3.

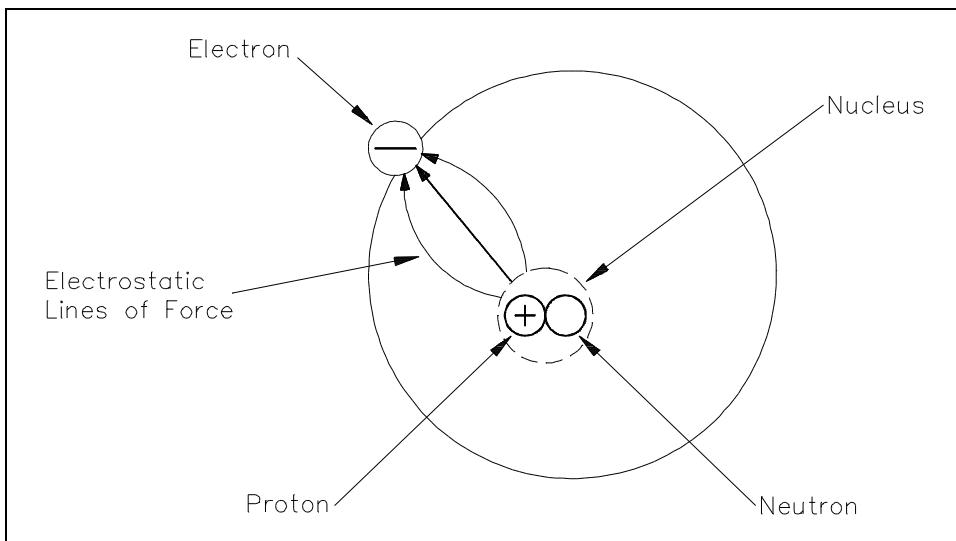


Figure 3 Electrostatic Force

Without this electrostatic force, the electron, which is traveling at high speed, could not stay in its orbit. Bodies that attract each other in this way are called charged bodies. As mentioned previously, the electron has a negative charge, and the nucleus (due to the proton) has a positive charge.

The First Law of Electrostatics

The negative charge of the electron is equal, but opposite to, the positive charge of the proton. These charges are referred to as electrostatic charges. In nature, unlike charges (like electrons and protons) attract each other, and like charges repel each other. These facts are known as the *First Law of Electrostatics* and are sometimes referred to as the law of electrical charges. This law should be remembered because it is one of the vital concepts in electricity.

Some atoms can lose electrons and others can gain electrons; thus, it is possible to transfer electrons from one object to another. When this occurs, the equal distribution of negative and positive charges no longer exists. One object will contain an excess of electrons and become negatively charged, and the other will become deficient in electrons and become positively charged. These objects, which can contain billions of atoms, will then follow the same law of electrostatics as the electron and proton example shown above. The electrons that can move around within an object are said to be free electrons and will be discussed in more detail in a later section. The greater the number of these free electrons an object contains, the greater its negative electric charge. Thus, the electric charge can be used as a measure of electrons.

Electrostatic Field

A special force is acting between the charged objects discussed above. Forces of this type are the result of an *electrostatic field* that exists around each charged particle or object. This electrostatic field, and the force it creates, can be illustrated with lines called "lines of force" as shown in Figure 4.

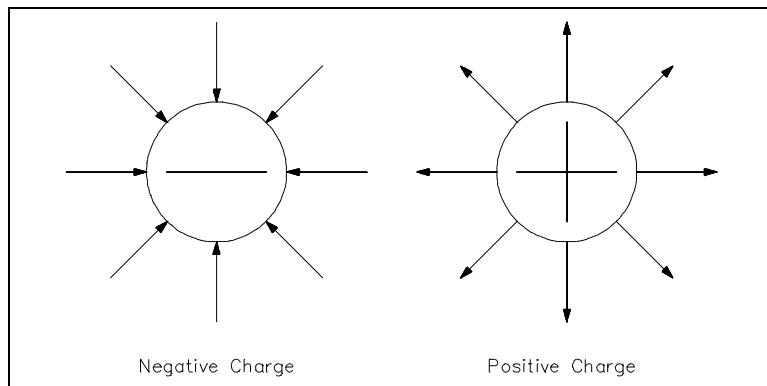


Figure 4 Electrostatic Field

Charged objects repel or attract each other because of the way these fields act together. This force is present with every charged object. When two objects of opposite charge are brought near one another, the electrostatic field is concentrated in the area between them, as shown in Figure 5. The direction of the small arrows shows the direction of the force as it would act upon an electron if it were released into the electric field.

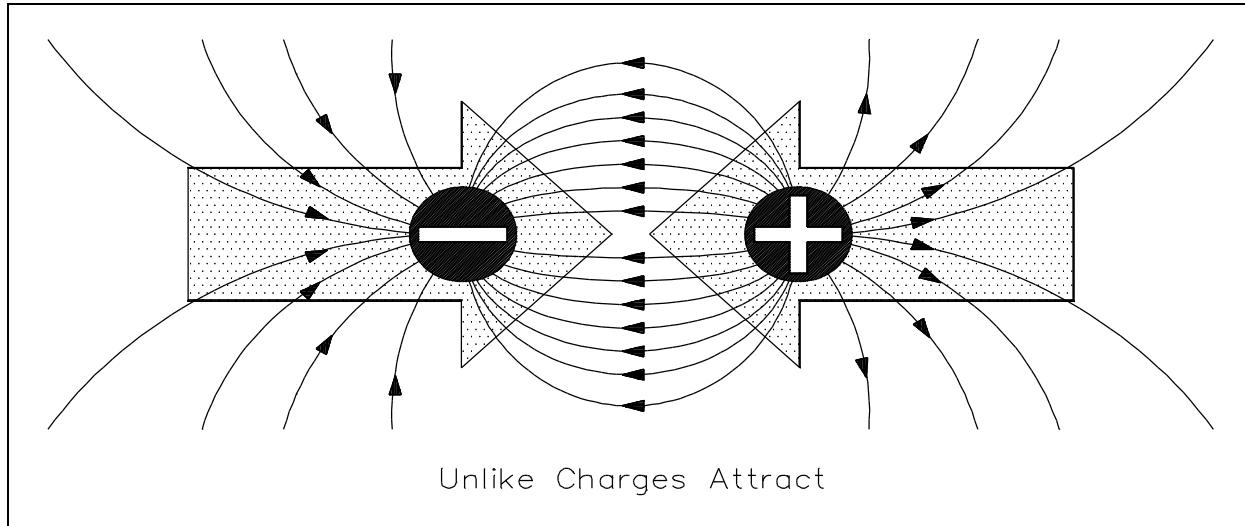


Figure 5 Electrostatic Field Between Two Charges of Opposite Polarity

When two objects of like charge are brought near one another, the lines of force repel each other, as shown in Figure 6.

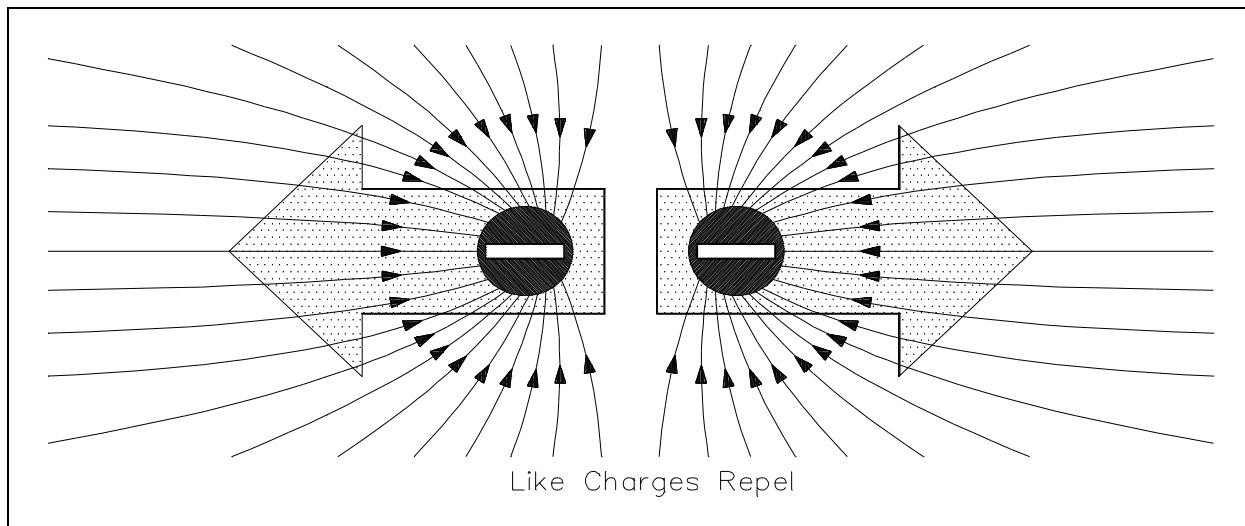


Figure 6 Electrostatic Field Between Two Charges of Like Polarity

The strength of the attraction or of the repulsion force depends upon two factors: (1) the amount of charge on each object, and (2) the distance between the objects. The greater the charge on the objects, the greater the electrostatic field. The greater the distance between the objects, the weaker the electrostatic field between them, and vice versa. This leads us to the law of electrostatic attraction, commonly referred to as Coulomb's Law of electrostatic charges, which states that the force of electrostatic attraction, or repulsion, is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them as shown in Equation 1-1.

$$F = K \frac{q_1 - q_2}{d^2} \quad (1-1)$$

where

F	= force of electrostatic attraction or repulsion (Newtons)
K	= constant of proportionality (Coulomb $^2/\text{N}\cdot\text{m}^2$)
q_1	= charge of first particle (Coulombs)
q_2	= charge of second particle (Coulombs)
d	= distance between two particles (Meters)

If q_1 and q_2 are both either positively or negatively charged, the force is repulsive. If q_1 and q_2 are opposite polarity or charge, the force is attractive.

Potential Difference

Potential difference is the term used to describe how large the electrostatic force is between two charged objects. If a charged body is placed between two objects with a potential difference, the charged body will try to move in one direction, depending upon the polarity of the object. If an electron is placed between a negatively-charged body and a positively-charged body, the action due to the potential difference is to push the electron toward the positively-charged object. The electron, being negatively charged, will be repelled from the negatively-charged object and attracted by the positively-charged object, as shown in Figure 7.

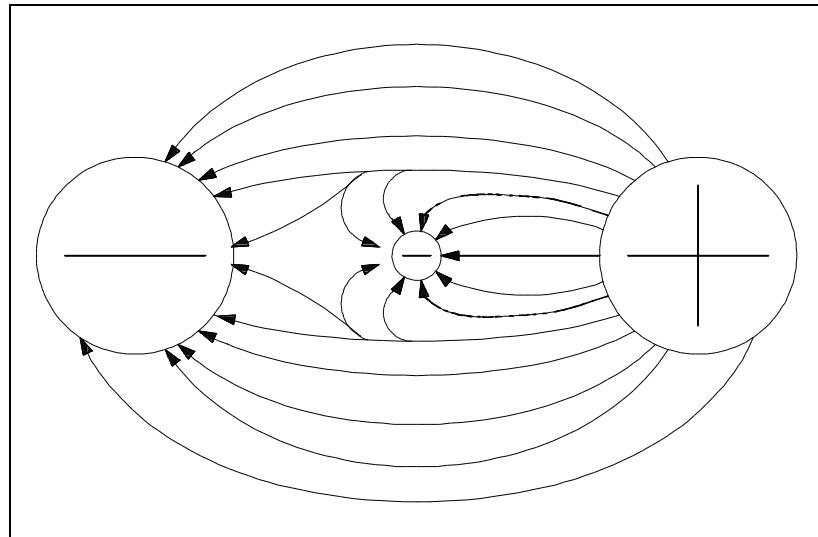


Figure 7 Potential Difference Between Two Charged Objects

Due to the force of its electrostatic field, these electrical charges have the ability to do work by moving another charged particle by attraction and/or repulsion. This ability to do work is called "potential"; therefore, if one charge is different from another, there is a potential difference between them. The sum of the potential differences of all charged particles in the electrostatic field is referred to as *electromotive force* (EMF).

The basic unit of measure of potential difference is the "volt." The symbol for potential difference is "V," indicating the ability to do the work of forcing electrons to move. Because the volt unit is used, potential difference is also called "voltage." The unit volt will be covered in greater detail in the next chapter.

Free Electrons

Electrons are in rapid motion around the nucleus. While the electrostatic force is trying to pull the nucleus and the electron together, the electron is in motion and trying to pull away. These two effects balance, keeping the electron in orbit. The electrons in an atom exist in different energy levels. The energy level of an electron is proportional to its distance from the nucleus. Higher energy level electrons exist in orbits, or shells, that are farther away from the nucleus. These shells nest inside one another and surround the nucleus. The nucleus is the center of all the shells. The shells are lettered beginning with the shell nearest the nucleus: K, L, M, N, O, P, and Q. Each shell has a maximum number of electrons it can hold. For example, the K shell will hold a maximum of two electrons and the L shell will hold a maximum of eight electrons. As shown in Figure 8, each shell has a specific number of electrons that it will hold for a particular atom.

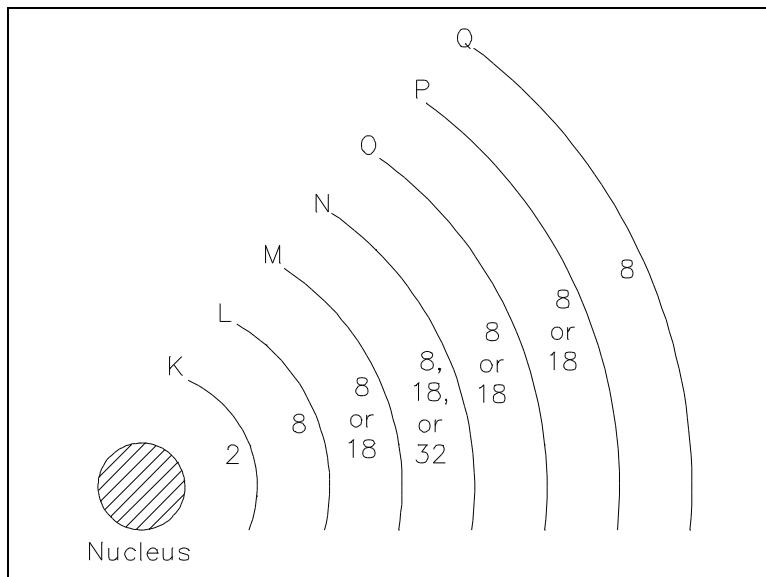


Figure 8 Energy Shells and Electron Quota

There are two simple rules concerning electron shells that make it possible to predict the electron distribution of any element:

1. The maximum number of electrons that can fit in the outermost shell of any atom is eight.
2. The maximum number of electrons that can fit in the next-to-outermost shell of any atom is 18.

An important point to remember is that when the outer shell of an atom contains eight electrons, the atom becomes very stable, or very resistant to changes in its structure. This also means that atoms with one or two electrons in their outer shell can lose electrons much more easily than atoms with full outer shells. The electrons in the outermost shell are called *valence electrons*. When external energy, such as heat, light, or electrical energy, is applied to certain materials, the electrons gain energy, become excited, and may move to a higher energy level. If enough energy is applied to the atom, some of the valence electrons will leave the atom. These electrons are called *free electrons*. It is the movement of free electrons that provides electric current in a metal conductor. An atom that has lost or gained one or more electrons is said to be *ionized* or to have an *ion change*. If the atom loses one or more electrons, it becomes positively charged and is referred to as a *positive ion*. If an atom gains one or more electrons, it becomes negatively charged and is referred to as a *negative ion*.

Summary

The important information contained in this chapter is summarized below.

Forces Around Atoms Summary

- Electrostatic Force - force that holds an electron in orbit around a nucleus
- Electrostatic Field - force acting between charged objects that causes them to repel or attract
- Potential Difference - measures how large the electrostatic force is between two charged objects. According to Coulomb's Law, charged bodies attract or repel each other with a force that is directly proportional to the product of their charges and is inversely proportional to the square of the distance between them.
- Electromotive Force (EMF) - sum of the potential differences of all charged particles in an electrostatic field
- Ion Charge - dependent on the loss or gain of free electrons (if an atom gains an electron - negative ion charge; if an atom loses an electron - positive ion charge)

ELECTRICAL TERMINOLOGY

Knowledge of key electrical terminology is necessary to fully understand principles in electrical science.

EO 1.2 **DEFINE the following terms:**

- a. **Conductor**
- b. **Insulator**
- c. **Resistor**
- d. **Electron current flow**
- e. **Conventional current flow**
- f. **Direct current (DC)**
- g. **Alternating current (AC)**
- h. **Ideal source**
- i. **Real source**

Conductors

Conductors are materials with electrons that are loosely bound to their atoms, or materials that permit free motion of a large number of electrons. Atoms with only one valence electron, such as copper, silver, and gold, are examples of good conductors. Most metals are good conductors.

Insulators

Insulators, or nonconductors, are materials with electrons that are tightly bound to their atoms and require large amounts of energy to free them from the influence of the nucleus. The atoms of good insulators have their valence shells filled with eight electrons, which means they are more than half filled. Any energy applied to such an atom will be distributed among a relatively large number of electrons. Examples of insulators are rubber, plastics, glass, and dry wood.

Resistors

Resistors are made of materials that conduct electricity, but offer opposition to current flow. These types of materials are also called *semiconductors* because they are neither good conductors nor good insulators. Semiconductors have more than one or two electrons in their valence shells, but less than seven or eight. Examples of semiconductors are carbon, silicon, germanium, tin, and lead. Each has four valence electrons.

Voltage

The basic unit of measure for potential difference is the *volt* (symbol V), and, because the volt unit is used, potential difference is called *voltage*. An object's electrical charge is determined by the number of electrons that the object has gained or lost. Because such a large number of electrons move, a unit called the "coulomb" is used to indicate the charge. One coulomb is equal to 6.28×10^{18} (billion, billion) electrons. For example, if an object gains one coulomb of negative charge, it has gained 6,280,000,000,000,000 extra electrons. A volt is defined as a difference of potential causing one coulomb of current to do one joule of work. A volt is also defined as that amount of force required to force one ampere of current through one ohm of resistance. The latter is the definition with which we will be most concerned in this module.

Current

The density of the atoms in copper wire is such that the valence orbits of the individual atoms overlap, causing the electrons to move easily from one atom to the next. Free electrons can drift from one orbit to another in a random direction. When a potential difference is applied, the direction of their movement is controlled. The strength of the potential difference applied at each end of the wire determines how many electrons change from a random motion to a more directional path through the wire. The movement or flow of these electrons is called *electron current flow* or just *current*.

To produce current, the electrons must be moved by a potential difference. The symbol for current is (I). The basic measurement for current is the ampere (A). One ampere of current is defined as the movement of one coulomb of charge past any given point of a conductor during one second of time.

If a copper wire is placed between two charged objects that have a potential difference, all of the negatively-charged free electrons will feel a force pushing them from the negative charge to the positive charge. This force opposite to the conventional direction of the electrostatic lines of force is shown in Figure 9.

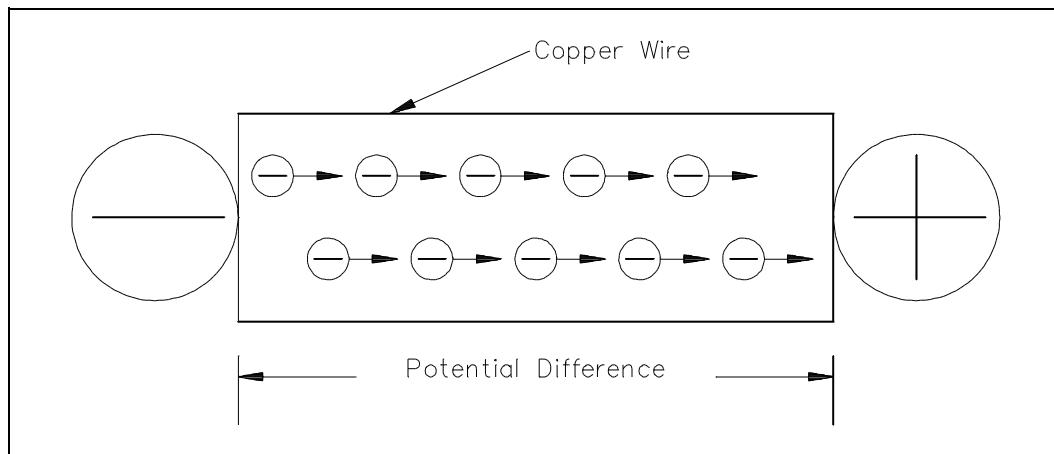


Figure 9 Electron Flow Through a Copper Wire with a Potential Difference

The direction of electron flow, shown in Figure 10, is from the negative (-) side of the battery, through the wire, and back to the positive (+) side of the battery. The direction of electron flow is from a point of negative potential to a point of positive potential. The solid arrow shown in Figure 10 indicates the direction of electron flow. As electrons vacate their atoms during electron current flow, positively charged atoms (holes) result. The flow of electrons in one direction causes a flow of positive charges. The direction of the positive charges is in the opposite direction of the electron flow. This flow of positive charges is known as *conventional current* and is shown in Figure 10 as a dashed arrow. All of the electrical effects of electron flow from negative to positive, or from a higher potential to a lower potential, are the same as those that would be created by a flow of positive charges in the opposite direction. Therefore, it is important to realize that both conventions are in use and that they are essentially equivalent; that is, all effects predicted are the same. In this text, we will be using electron flow in our discussions.

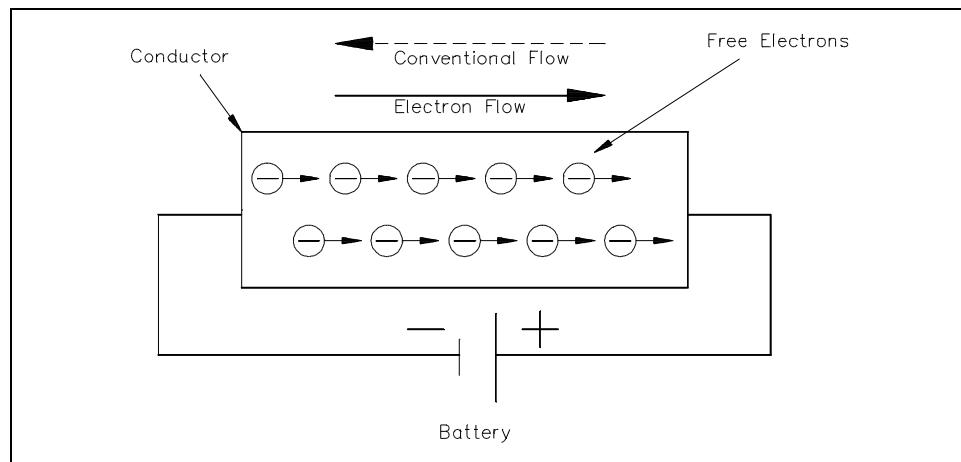


Figure 10 Potential Difference Across a Conductor Causes a Current to Flow

Generally, electric current flow can be classified as one of two general types: *Direct Current* (DC) or *Alternating Current* (AC). A direct current flows continuously in the same direction. An alternating current periodically reverses direction. We will be studying DC and AC current in more detail later in this text. An example of DC current is that current obtained from a battery. An example of AC current is common household current.

Real and Ideal Sources

An *ideal source* is a theoretical concept of an electric current or voltage supply (such as a battery) that has no losses and is a perfect voltage or current supply. Ideal sources are used for analytical purposes only since they cannot occur in nature.

A *real source* is a real life current or voltage supply that has some losses associated with it.

Summary

The important information contained in this chapter is summarized below.

Terminology Summary

- Conductor - material with electrons loosely bound to its atoms or that permits free motion of large number of electrons
- Insulator - material with electrons tightly bound to its atoms; requires large amounts of energy to free electrons from its nuclei
- Resistor - material that conducts electricity, but opposes current flow
- Electron Current Flow - current flow from negative to positive potentials
- Conventional Current Flow - current flow from positive to negative potentials
- Direct Current - current flow continuously in the same direction
- Alternating Current - current flow periodically reverses direction
- Ideal Source - theoretical current or voltage supply with no losses
- Real Source - actual current or voltage supply with losses

UNITS OF ELECTRICAL MEASUREMENT

Using Ohm's Law and the System Internationale (SI) Metric System, electrical measuring units can be derived.

EO 1.3 **DESCRIBE** the following electrical parameters, including the unit of measurement and the relationship to other parameters.

- a. **Voltage**
- b. **Current**
- c. **Resistance**
- d. **Conductance**
- e. **Power**
- f. **Inductance**
- g. **Capacitance**

EO 1.4 **Given any two of the three component values of Ohm's Law, DETERMINE the unknown component value.**

System Internationale (SI) Metric System

Electrical units of measurement are based on the International (metric) System, also known as the SI System. Units of electrical measurement include the following:

- Ampere
- Volt
- Ohm
- Siemens
- Watt
- Henry
- Farad

Appendix A provides more information concerning the metric system, metric prefixes, and powers of 10 that are used in electrical measuring units.

Voltage

Voltage, electromotive force (emf), or potential difference, is described as the pressure or force that causes electrons to move in a conductor. In electrical formulas and equations, you will see voltage symbolized with a capital E, while on laboratory equipment or schematic diagrams, the voltage is often represented with a capital V.

Current

Electron *current*, or amperage, is described as the movement of free electrons through a conductor. In electrical formulas, current is symbolized with a capital I, while in the laboratory or on schematic diagrams, it is common to use a capital A to indicate amps or amperage (amps).

Resistance

Now that we have discussed the concepts of voltage and current, we are ready to discuss a third key concept called resistance. *Resistance* is defined as the opposition to current flow. The amount of opposition to current flow produced by a material depends upon the amount of available free electrons it contains and the types of obstacles the electrons encounter as they attempt to move through the material. Resistance is measured in ohms and is represented by the symbol (R) in equations. One ohm is defined as that amount of resistance that will limit the current in a conductor to one ampere when the potential difference (voltage) applied to the conductor is one volt. The shorthand notation for ohm is the Greek letter capital omega (Ω). If a voltage is applied to a conductor, current flows. The amount of current flow depends upon the resistance of the conductor. The lower the resistance, the higher the current flow for a given amount of voltage. The higher the resistance, the lower the current flow.

Ohm's Law

In 1827, George Simon Ohm discovered that there was a definite relationship between voltage, current, and resistance in an electrical circuit. Ohm's Law defines this relationship and can be stated in three ways.

1. Applied voltage equals circuit current times the circuit resistance. Equation (1-2) is a mathematical representation of this concept.

$$E = I \times R \quad \text{or} \quad E = IR \quad (1-2)$$

2. Current is equal to the applied voltage divided by the circuit resistance. Equation (1-3) is a mathematical representation of this concept.

$$I = \frac{E}{R} \quad (1-3)$$

3. Resistance of a circuit is equal to the applied voltage divided by the circuit current. Equation (1-4) is a mathematical representation of this concept.

$$R \text{ (or } \Omega) = \frac{E}{I} \quad (1-4)$$

where

I = current (A)

E = voltage (V)

R = resistance (Ω)

If any two of the component values are known, the third can be calculated.

Example 1: Given that $I = 2$ A, $E = 12$ V, find the circuit resistance.

Solution:

Since applied voltage and circuit current are known, use Ohm's Law to solve for resistance.

$$R = \frac{E}{I}$$

$$R = \frac{12 \text{ V}}{2 \text{ A}} = 6 \text{ } \Omega$$

Example 2: Given $E = 260$ V and $R = 240 \text{ } \Omega$, what current will flow through a circuit?

Solution:

Since applied voltage and resistance are known, use Ohm's Law to solve for current.

$$I = \frac{E}{R}$$

$$I = \frac{260 \text{ V}}{240 \text{ } \Omega} = 1.08\overline{3} \text{ A}$$

Example 3: Find the applied voltage, when given circuit resistance of 100Ω and circuit current of 0.5 amps.

Solution:

Since circuit resistance and circuit current are known, use Ohm's Law to solve for applied voltage.

$$E = IR$$

$$E = (0.5 \text{ A})(100 \Omega) = 50 \text{ V}$$

Conductance

The word "reciprocal" is sometimes used to mean "the opposite of." The opposite, or reciprocal, of resistance is called *conductance*. As described above, resistance is the opposition to current flow. Since resistance and conductance are opposites, conductance can be defined as the ability to conduct current. For example, if a wire has a high conductance, it will have low resistance, and vice-versa. Conductance is found by taking the reciprocal of the resistance. The unit used to specify conductance is called "mho," which is ohm spelled backwards. The symbol for "mho" is the Greek letter omega inverted (Ω). The symbol for conductance when used in a formula is G. Equation (1-5) is the mathematical representation of conductance obtained by relating the definition of conductance ($1/R$) to Ohm's Law, Equation (1-4).

$$G = \frac{1}{\text{RESISTANCE}} = \frac{I}{E} \quad (1-5)$$

Example: If a resistor (R) has five ohms, what will its conductance (G) be in mhos?

Solution:

$$G \text{ (or } \Omega) = \frac{1}{R} = \frac{1}{5} = 0.2 \Omega$$

Power

Electricity is generally used to do some sort of work, such as turning a motor or generating heat. Specifically, *power* is the rate at which work is done, or the rate at which heat is generated. The unit commonly used to specify electric power is the watt. In equations, you will find power abbreviated with the capital letter P, and watts, the units of measure for power, are abbreviated with the capital letter W. Power is also described as the current (I) in a circuit times the voltage (E) across the circuit. Equation (1-6) is a mathematical representation of this concept.

$$P = I \times E \quad \text{or} \quad P = IE \quad (1-6)$$

Using Ohm's Law for the value of voltage (E),

$$E = I \times R$$

and using substitution laws,

$$P = I \times (I \times R)$$

power can be described as the current (I) in a circuit squared times the resistance (R) of the circuit. Equation (1-7) is the mathematical representation of this concept.

$$P = I^2 R \quad (1-7)$$

Inductance

Inductance is defined as the ability of a coil to store energy, induce a voltage in itself, and oppose changes in current flowing through it. The symbol used to indicate inductance in electrical formulas and equations is a capital L. The units of measurement are called henries. The unit henry is abbreviated by using the capital letter H. One henry is the amount of inductance (L) that permits one volt to be induced (V_L) when the current through the coil changes at a rate of one ampere per second. Equation (1-8) is the mathematical representation of the rate of change in current through a coil per unit time.

$$\left(\frac{\Delta I}{\Delta t} \right) \quad (1-8)$$

Equation (1-9) is the mathematical representation for the voltage V_L induced in a coil with inductance L. The negative sign indicates that voltage induced opposes the change in current through the coil per unit time ($\Delta I / \Delta t$).

$$V_L = -L \left(\frac{\Delta I}{\Delta t} \right) \quad (1-9)$$

Inductance will be studied in further detail later in this text.

Capacitance

Capacitance is defined as the ability to store an electric charge and is symbolized by the capital letter C. Capacitance (C), measured in farads, is equal to the amount of charge (Q) that can be stored in a device or capacitor divided by the voltage (E) applied across the device or capacitor plates when the charge was stored. Equation (1-10) is the mathematical representation for capacitance.

$$C = \frac{Q}{E} \quad (1-10)$$

Summary

The important information contained in this chapter is summarized below.

Electrical Units Summary

<u>Parameter</u>	<u>Measuring Unit</u>	<u>Relationship</u>
Voltage	volt (V or E)	$E = I \times R$
Current	amp (I)	$I = \frac{E}{R}$
Resistance	ohm (R or Ω)	$R = \frac{E}{I}$
Conductance	mho (G or \mathfrak{G})	$G = \frac{I}{R} = \frac{I}{E}$
Power	watt (W)	$P = I \times E$ or $P = I^2R$
Inductance	henry (L or H)	$V_L = -L \left(\frac{\Delta I}{\Delta t} \right)$
Capacitance	farad (C)	$C = \frac{Q}{E}$ (Q = charge)

METHODS OF PRODUCING VOLTAGE (ELECTRICITY)

This section provides information on the following methods of producing electricity:

- *Electrochemistry*
- *Static (friction)*
- *Induction (magnetism)*
- *Piezoelectric (pressure)*
- *Thermal (heat)*
- *Light*
- *Thermionic emission*

EO 1.5 DESCRIBE how the following methods produce a voltage:

- a. **Electrochemistry**
- b. **Static electricity**
- c. **Magnetic induction**
- d. **Piezoelectric effect**
- e. **Thermoelectricity**
- f. **Photoelectric effect**
- g. **Thermionic emission**

Electrochemistry

Chemicals can be combined with certain metals to cause a chemical reaction that will transfer electrons to produce electrical energy. This process works on the *electrochemistry* principle. One example of this principle is the voltaic chemical cell, shown in Figure 11. A chemical reaction produces and maintains opposite charges on two dissimilar metals that serve as the positive and negative terminals. The metals are in contact with an electrolyte solution. Connecting together more than one of these cells will produce a battery.

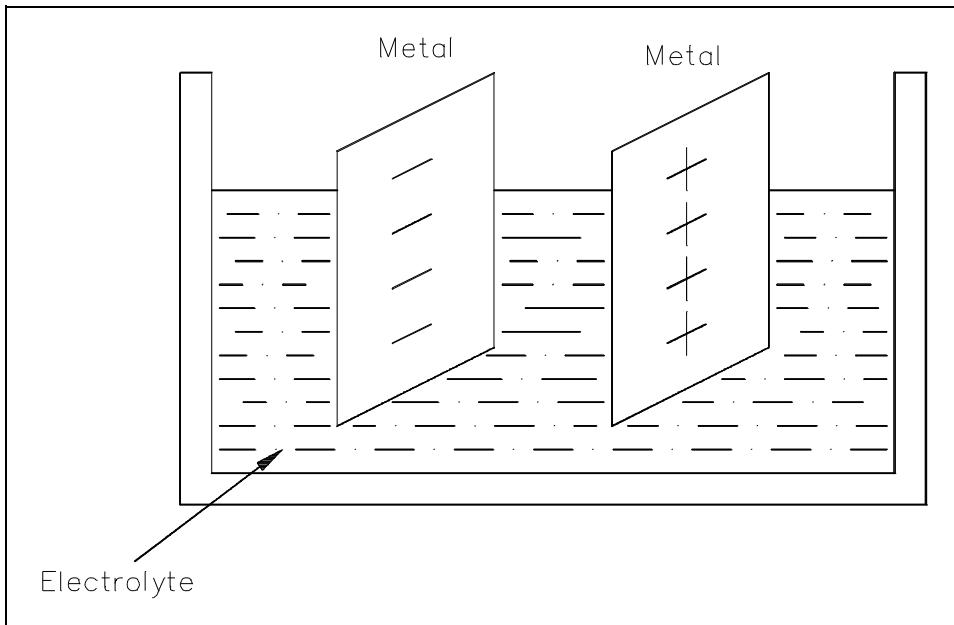


Figure 11 Voltaic Chemical Cell

Example: A battery can maintain a potential difference between its positive and negative terminals by chemical action. Various types of cells and batteries will be studied in more detail in Module 4, Batteries.

Static Electricity

Atoms with the proper number of electrons in orbit around them are in a neutral state, or have a "zero charge." A body of matter consisting of these atoms will neither attract nor repel other matter that is in its vicinity. If electrons are removed from the atoms in this body of matter, as happens due to friction when one rubs a glass rod with a silk cloth, it will become electrically positive as shown in Figure 12. If this body of matter (e.g., glass rod) comes near, but not in contact with, another body having a normal charge, an electric force is exerted between them because of their unequal charges. The existence of this force is referred to as *static electricity* or *electrostatic force*.

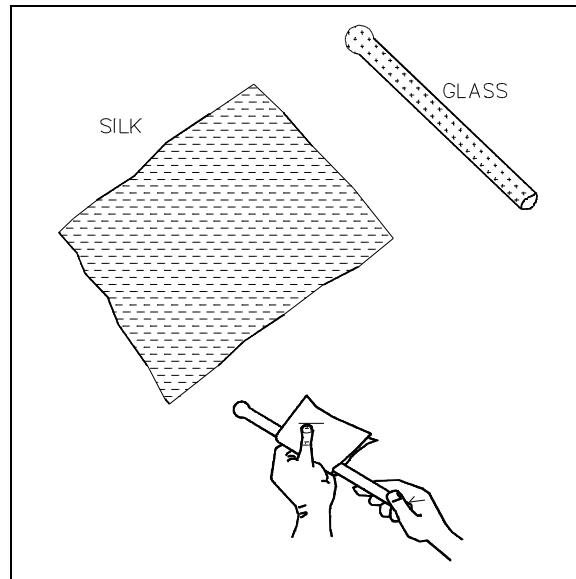


Figure 12 Static Electricity

Example: Have you ever walked across a carpet and received a shock when you touched a metal door knob? Your shoe soles built up a charge by rubbing on the carpet, and this charge was transferred to your body. Your body became positively charged and, when you touched the zero-charged door knob, electrons were transferred to your body until both you and the door knob had equal charges.

Magnetic Induction

A generator is a machine that converts mechanical energy into electrical energy by using the principle of *magnetic induction*. Magnetic induction is used to produce a voltage by rotating coils of wire through a stationary magnetic field, as shown in Figure 13, or by rotating a magnetic field through stationary coils of wire. This is one of the most useful and widely-employed applications of producing vast quantities of electric power. Magnetic induction will be studied in more detail in the next two chapters "Magnetism," and "Magnetic Circuits."

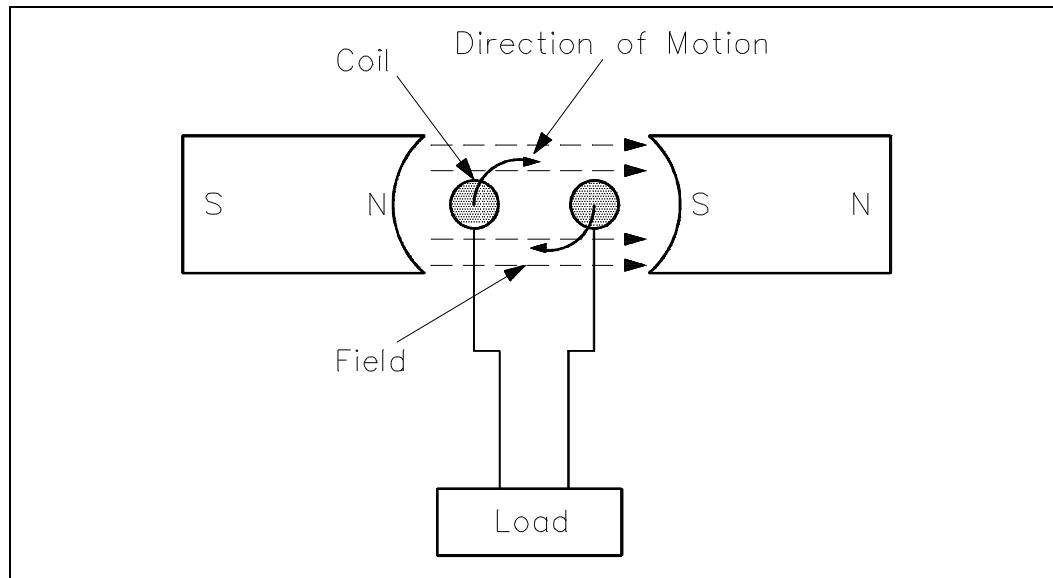


Figure 13 Generator - Electromagnetic Induction

Piezoelectric Effect

By applying pressure to certain crystals (such as quartz or Rochelle salts) or certain ceramics (like barium titanate), electrons can be driven out of orbit in the direction of the force. Electrons leave one side of the material and accumulate on the other side, building up positive and negative charges on opposite sides, as shown in Figure 14. When the pressure is released, the electrons return to their orbits. Some materials will react to bending pressure, while others will respond to twisting pressure. This generation of voltage is known as the *piezoelectric effect*. If external wires are connected while pressure and voltage are present, electrons will flow and current will be produced. If the pressure is held constant, the current will flow until the potential difference is equalized.

When the force is removed, the material is decompressed and immediately causes an electric force in the opposite direction. The power capacity of these materials is extremely small. However, these materials are very useful because of their extreme sensitivity to changes of mechanical force.

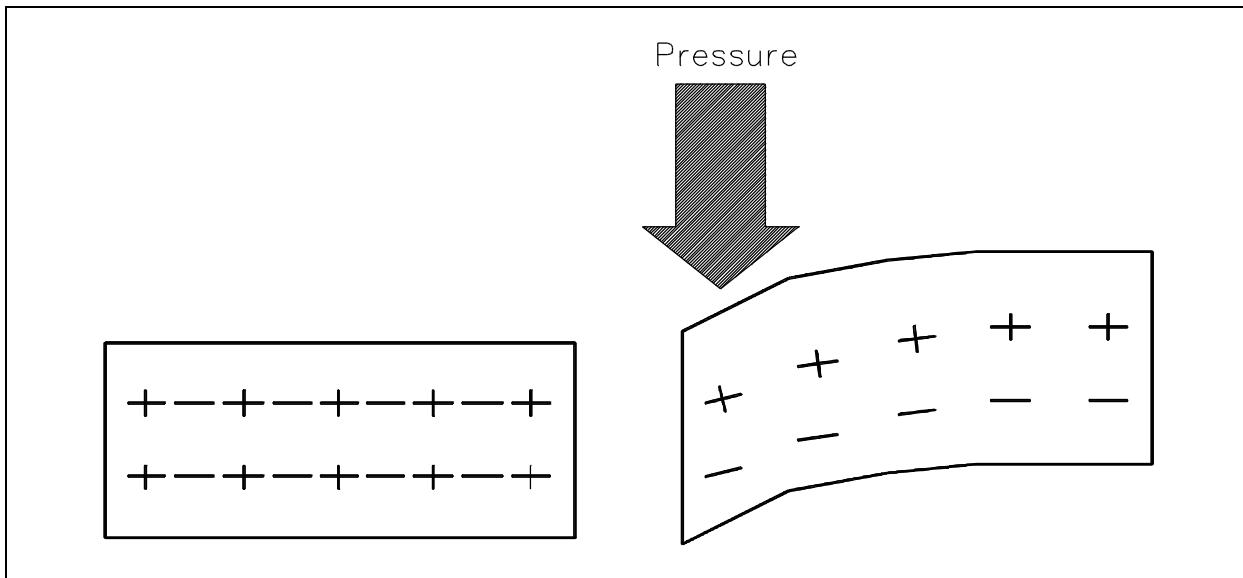


Figure 14 Pressure Applied to Certain Crystals Produces an Electric Charge

Example: One example is the crystal phonograph cartridge that contains a Rochelle salt crystal. A phonograph needle is attached to the crystal. As the needle moves in the grooves of a record, it swings from side to side, applying compression and decompression to the crystal. This mechanical motion applied to the crystal generates a voltage signal that is used to reproduce sound.

Thermoelectricity

Some materials readily give up their electrons and others readily accept electrons. For example, when two dissimilar metals like copper and zinc are joined together, a transfer of electrons can take place. Electrons will leave the copper atoms and enter the zinc atoms. The zinc gets a surplus of electrons and becomes negatively charged. The copper loses electrons and takes on a positive charge. This creates a voltage potential across the junction of the two metals. The heat energy of normal room temperature is enough to make them release and gain electrons, causing a measurable voltage potential. As more heat energy is applied to the junction, more electrons are released, and the voltage potential becomes greater, as shown in Figure 15. When heat is removed and the junction cools, the charges will dissipate and the voltage potential will decrease. This process is called *thermoelectricity*. A device like this is generally referred to as a "thermocouple."

The thermoelectric voltage in a thermocouple is dependent upon the heat energy applied to the junction of the two dissimilar metals. Thermocouples are widely used to measure temperature and as heat-sensing devices in automatic temperature controlled equipment.

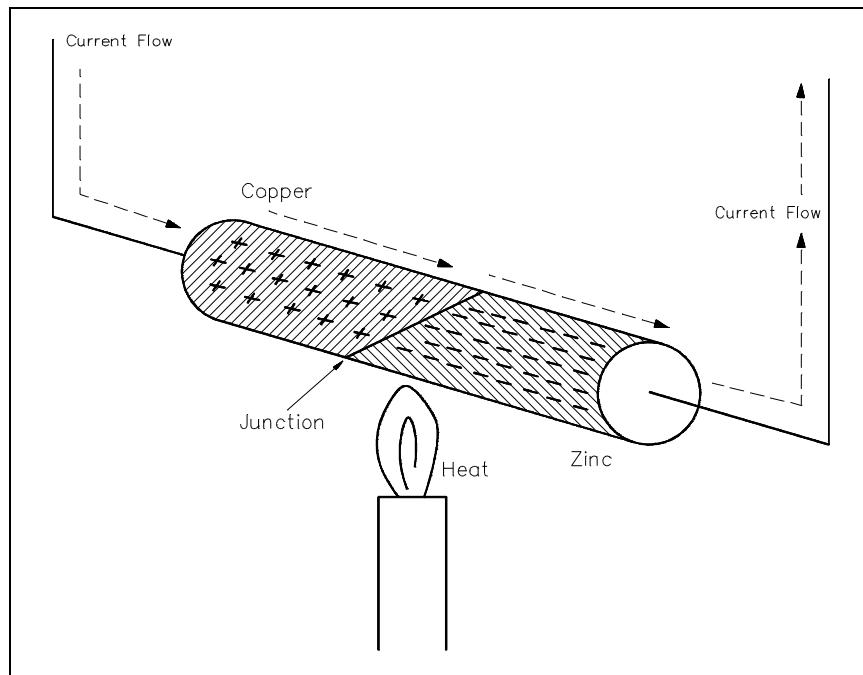


Figure 15 Heat Energy Causes Copper to Give up Electrons to Zinc

Thermocouple power capacities are very small compared to some other sources, but are somewhat greater than those of crystals.

Generally speaking, a thermocouple can be subjected to higher temperatures than ordinary mercury or alcohol thermometers.

Photoelectric Effect

Light is a form of energy and is considered by many scientists to consist of small particles of energy called photons. When the photons in a light beam strike the surface of a material, they release their energy and transfer it to the atomic electrons of the material. This energy transfer may dislodge electrons from their orbits around the surface of the substance. Upon losing electrons, the photosensitive (light sensitive) material becomes positively charged and an electric force is created, as shown in Figure 16.

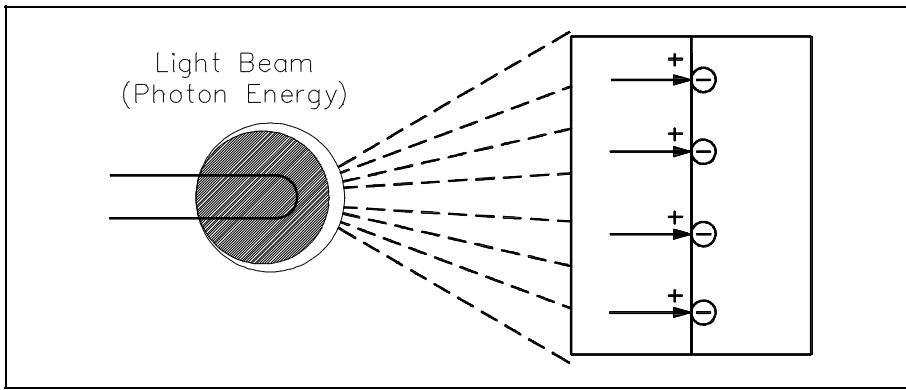


Figure 16 Producing Electricity from Light Using a Photovoltaic Cell

This phenomenon is called the *photoelectric effect* and has wide applications in electronics, such as photoelectric cells, photovoltaic cells, optical couplers, and television camera tubes. Three uses of the photoelectric effect are described below.

- Photovoltaic: The light energy in one of two plates that are joined together causes one plate to release electrons to the other. The plates build up opposite charges, like a battery (Figure 16).
- Photoemission: The photon energy from a beam of light could cause a surface to release electrons in a vacuum tube. A plate would then collect the electrons.
- Photoconduction: The light energy applied to some materials that are normally poor conductors causes free electrons to be produced in the materials so that they become better conductors.

Thermionic Emission

A thermionic energy converter is a device consisting of two electrodes placed near one another in a vacuum. One electrode is normally called the cathode, or emitter, and the other is called the anode, or plate. Ordinarily, electrons in the cathode are prevented from escaping from the surface by a potential-energy barrier. When an electron starts to move away from the surface, it induces a corresponding positive charge in the material, which tends to pull it back into the surface. To escape, the electron must somehow acquire enough energy to overcome this energy barrier. At ordinary temperatures, almost none of the electrons can acquire enough energy to escape. However, when the cathode is very hot, the electron energies are greatly increased by thermal motion. At sufficiently high temperatures, a considerable number of electrons are able to escape. The liberation of electrons from a hot surface is called *thermionic emission*.

The electrons that have escaped from the hot cathode form a cloud of negative charges near it called a space charge. If the plate is maintained positive with respect to the cathode by a battery, the electrons in the cloud are attracted to it. As long as the potential difference between the electrodes is maintained, there will be a steady current flow from the cathode to the plate.

The simplest example of a thermionic device is a vacuum tube diode in which the only electrodes are the cathode and plate, or anode, as shown in Figure 17. The diode can be used to convert alternating current (AC) flow to a pulsating direct current (DC) flow.

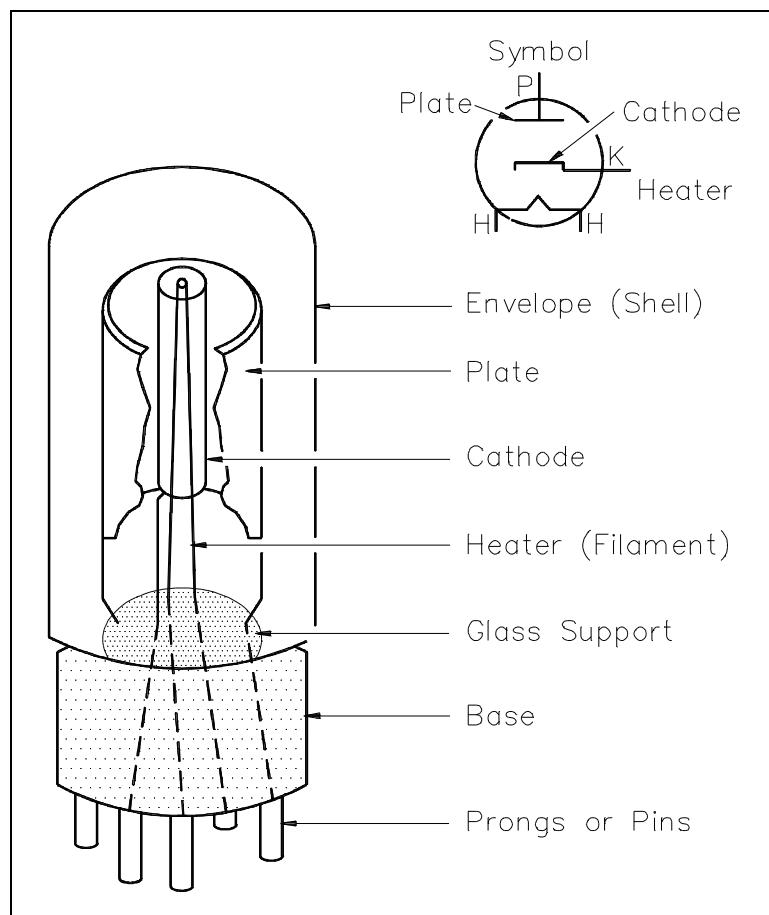


Figure 17 Vacuum Tube Diode

Summary

The important information contained in this chapter is summarized below.

Methods of Producing Electricity Summary

- Electrochemistry - Combining chemicals with certain metals causes a chemical reaction that transfers electrons.
- Static electricity - When an object with a normally neutral charge loses electrons, due to friction, and comes in contact with another object having a normal charge, an electric charge is exerted between the two objects.
- Magnetic induction - Rotating coils of wire through a stationary magnetic field or by rotating a magnetic field through a stationary coil of wire produces a potential.
- Piezoelectric effect - Bending or twisting certain materials will cause electrons to drive out of orbit in the direction of the force. When the force is released, the electrons return to their original orbit.
- Thermoelectricity - Heating two joined dissimilar materials will cause a transfer of electrons between the materials setting up a current flow.
- Photoelectric effect - Dislodging of electrons from their orbits by light beams creates positively-charged objects.
- Thermionic emission - Freeing electrons from a hot surface causes electrons to escape.

MAGNETISM

Certain metals and metallic oxides have the ability to attract other metals. This property is called magnetism, and the materials which have this property are called magnets. Some magnets are found naturally while others must be manufactured.

EO 1.6 **DEFINE** the following terms:

- a. **Magnetic flux**
- b. **Magnetic flux density**
- c. **Weber**
- d. **Permeability**
- e. **Magnetomotive force (mmf)**
- f. **Ampere turns**
- g. **Field intensity**
- h. **Reluctance**

EO 1.7 **DESCRIBE** the following materials as they relate to permeability, including an example and an approximate relative permeability.

- a. **Ferromagnetic materials**
- b. **Paramagnetic materials**
- c. **Diamagnetic materials**

Magnetism

Magnetism is a result of electrons spinning on their own axis around the nucleus (Figure 18).

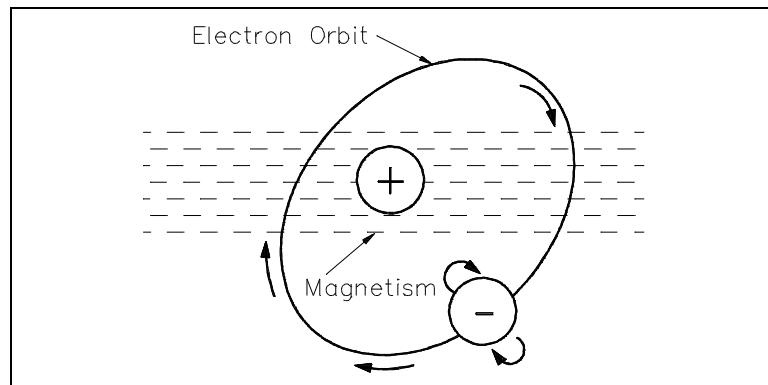


Figure 18 Electron Spinning Around Nucleus
Produces Magnetic Field

In magnetic materials, the atoms have certain areas called domains. These domains are aligned such that their electrons tend to spin in the same direction (Figure 19).

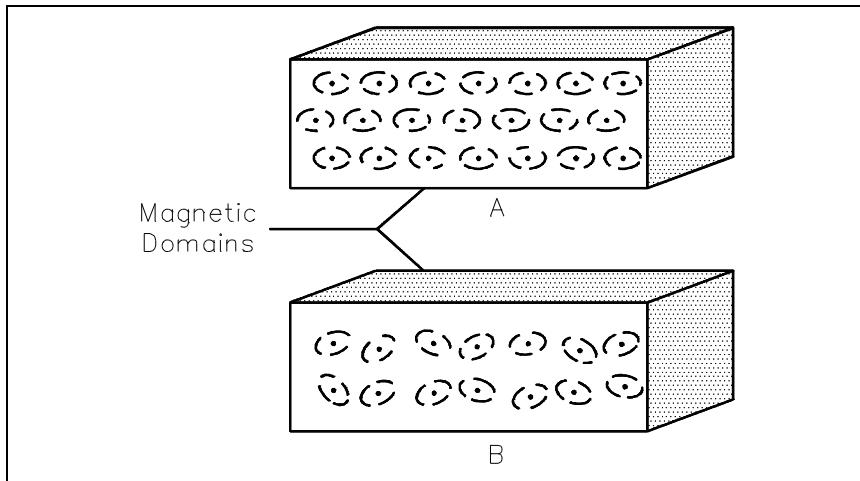


Figure 19 Magnetic Domains

The alignment of these domains results in the formation of magnetic poles at each end of the magnet. These poles are called the north pole and the south pole. The law of magnetism states that like magnetic poles repel and unlike magnetic poles attract one another (Figure 20).

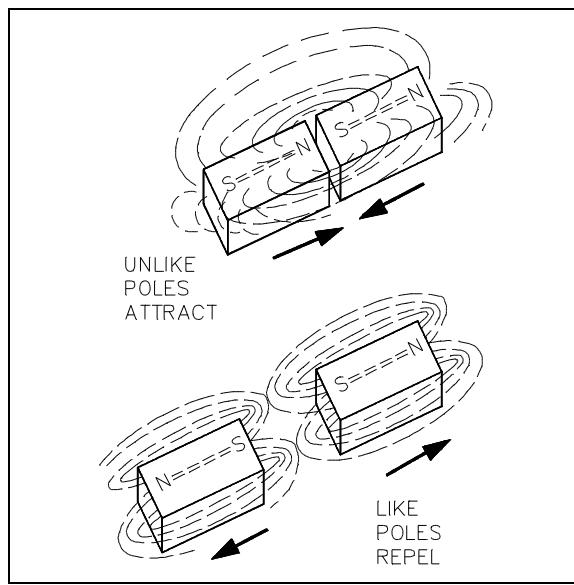


Figure 20 The Law of Magnetic Attraction and Repulsion

Magnetic Flux

The group of magnetic field lines emitted outward from the north pole of a magnet is called *magnetic flux*. The symbol for magnetic flux is Φ (phi).

The SI unit of magnetic flux is the weber (Wb). One *weber* is equal to 1×10^8 magnetic field lines.

Example: If a magnetic flux (Φ) has 5,000 lines, find the number of webers.

$$\Phi = \frac{5000 \text{ lines}}{1 \times 10^8 \text{ lines/Wb}} = \frac{5 \times 10^3}{10^8} = 50 \times 10^{-6} \text{ Wb} = 50 \mu\text{Wb}$$

Magnetic Flux Density

Magnetic flux density is the amount of magnetic flux per unit area of a section, perpendicular to the direction of flux. Equation (1-11) is the mathematical representation of magnetic flux density.

$$B = \frac{\Phi}{A} \quad (1-11)$$

where

B = magnetic flux density in teslas (T)

Φ = magnetic flux in webers (Wb)

A = area in square meters (m^2)

The result is that the SI unit for flux density is webers per square meter $\left(\frac{\text{Wb}}{\text{m}^2}\right)$. One weber per square meter equals one tesla.

Example: Find the flux density in teslas, when the flux is 800 μ Wb and the area is 0.004 m^2 .

$$\text{Given: } \Phi = 800 \mu\text{Wb} = 8 \times 10^{-4} \text{ Wb}$$

$$A = 0.0004 \text{ m}^2 = 4 \times 10^{-4} \text{ m}^2$$

$$B = \frac{\Phi}{A} = \frac{8 \times 10^{-4} \text{ Wb}}{4 \times 10^{-4} \text{ m}^2} = 2 \text{ Wb/m}^2$$

Magnetic Materials

Magnetic materials are those materials that can be either attracted or repelled by a magnet and can be magnetized themselves. The most commonly used magnetic materials are iron and steel. A permanent magnet is made of a very hard magnetic material, such as cobalt steel, that retains its magnetism for long periods of time when the magnetizing field is removed. A temporary magnet is a material that will not retain its magnetism when the field is removed.

Permeability (μ) refers to the ability of a material to concentrate magnetic lines of flux. Those materials that can be easily magnetized are considered to have a high permeability. Relative permeability is the ratio of the permeability of a material to the permeability of a vacuum (μ_o). The symbol for relative permeability is μ_R (mu).

$$\mu_R = \frac{\mu}{\mu_o} \text{ where } \mu_o = 4\pi 10^{-7} \text{ H/m} \quad (1-12)$$

Magnetic materials are classified as either magnetic or nonmagnetic based on the highly magnetic properties of iron. Because even weak magnetic materials may serve a useful purpose in some applications, classification includes the three groups described below.

Ferromagnetic Materials: Some of the ferromagnetic materials used are iron, steel, nickel, cobalt, and the commercial alloys, alnico and peralloy. Ferrites are nonmagnetic, but have the ferromagnetic properties of iron. Ferrites are made of ceramic material and have relative permeabilities that range from 50 to 200. They are commonly used in the coils for RF (radio frequency) transformers.

Paramagnetic Materials: These are materials such as aluminum, platinum, manganese, and chromium. These materials have a relative permeability of slightly more than one.

Diamagnetic Materials: These are materials such as bismuth, antimony, copper, zinc, mercury, gold, and silver. These materials have a relative permeability of less than one.

Electromagnetism

The relationship between magnetism and electrical current was discovered by a Danish scientist named Oersted in 1819. He found that if an electric current was caused to flow through a conductor, the conductor produced a magnetic field around that conductor (Figure 21).

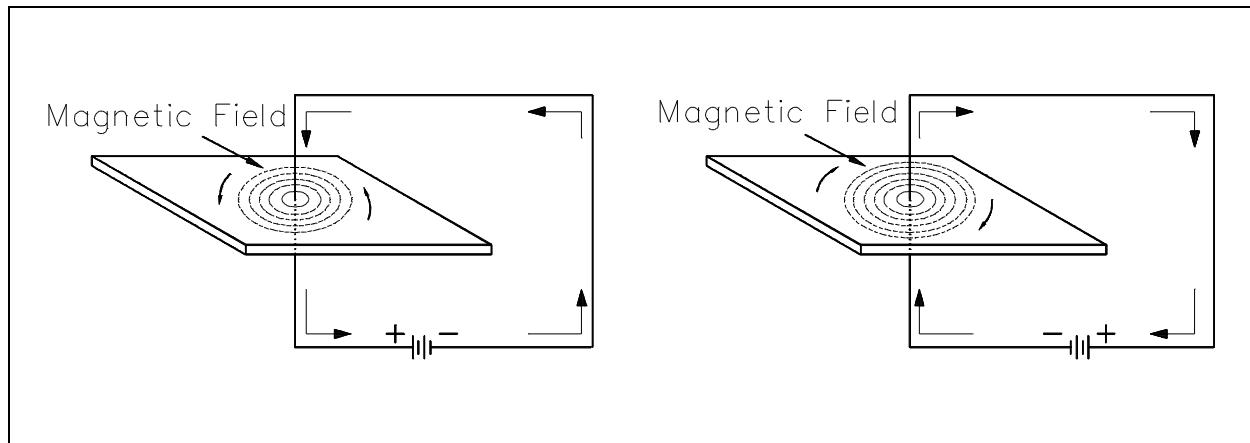


Figure 21 The Magnetic Field Produced by Current in a Conductor

Polarity of a Single Conductor

A convenient way to determine the relationship between the current flow through a conductor and the direction of the magnetic lines of force around the conductor is the left-hand rule for current carrying conductors, as illustrated in Figure 22. The student should verify that the left-hand rule holds true for the examples shown in Figure 21.

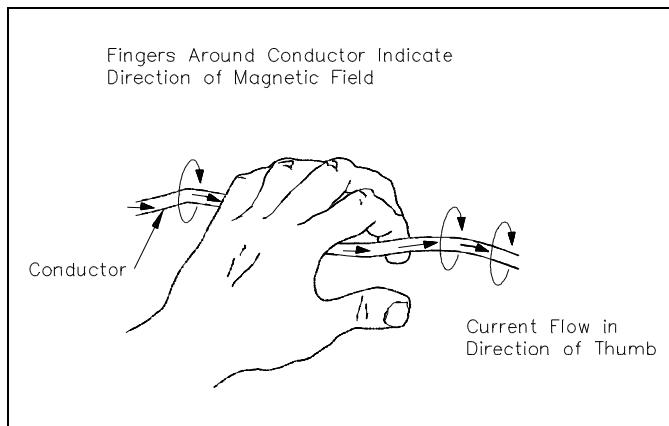


Figure 22 Left-hand Rule for Current Carrying Conductors

Magnetic Field and Polarity of a Coil

Bending a straight conductor into a loop has two results: (1) magnetic field lines become more dense inside the loop, and (2) all lines inside the loop are aiding in the same direction.

When a conductor is shaped into several loops, it is considered to be a coil. To determine the polarity of a coil, use the left-hand rule for coils (Figure 23).

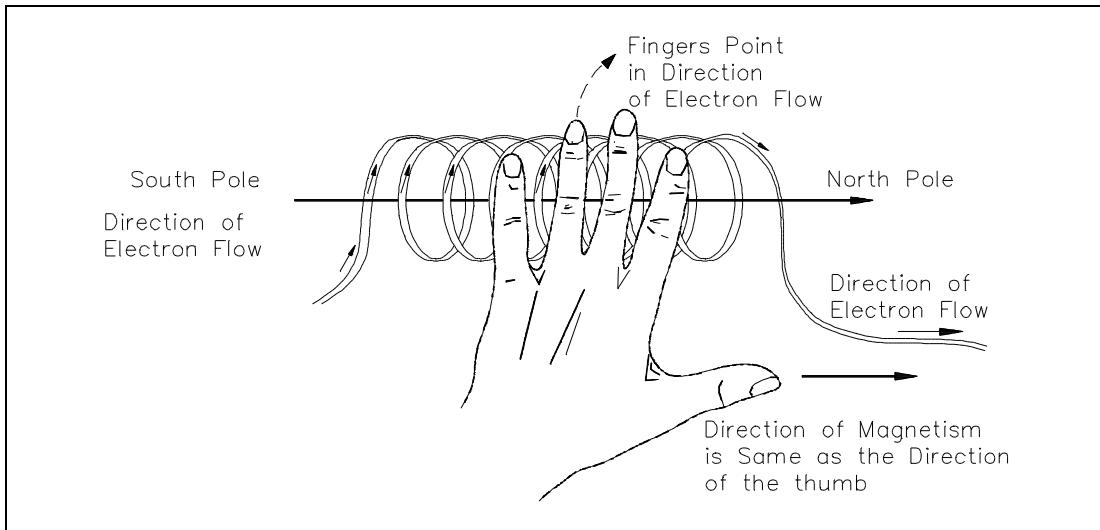


Figure 23 Left-hand Rule for Coils

Adding an iron core inside of a coil will increase the flux density. The polarity of the iron core will be the same as that of the coil. Current flow is from the negative side of the voltage source, through the coil, and back to the positive side of the source (Figure 24).

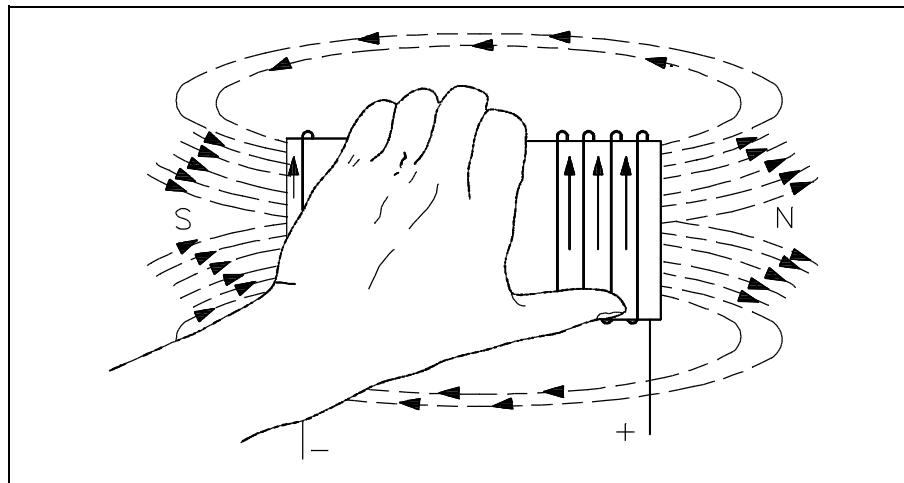


Figure 24 Left-hand Rule to Find North Pole of an Electromagnet

Magnetomotive Force

Magnetomotive force (mmf) is the strength of a magnetic field in a coil of wire. This is dependent on how much current flows in the turns of coil: the more current, the stronger the magnetic field; the more turns of wire, the more concentrated the lines of force. The current times the number of turns of the coil is expressed in units called "ampere-turns" (At), also known as mmf. Equation (1-13) is the mathematical representation for ampere-turns (At).

$$F_m = \text{ampere-turns} = NI \quad (1-13)$$

where

F_m = magnetomotive force (mmf)

N = number of turns

I = current

Example: Calculate the ampere-turns for a coil with 1000 turns and a 5 mA current.

$$N = 1000 \text{ turns and } I = 5 \text{ mA}$$

substitute

$$N = 1000 \text{ turns and } I = 5 \times 10^{-3}$$

$$NI = 1000 (5 \times 10^{-3}) = 5 \text{ At}$$

Field Intensity

When a coil with a certain number of ampere-turns is stretched to twice its length, the magnetic *field intensity*, or the concentration of its magnetic lines of force, will be half as great. Therefore, field intensity depends on the length of the coil. Equation (1-14) is the mathematical representation for field intensity, which is related to magnetomotive force as shown.

$$H = \frac{F_M}{L} = \frac{NI}{L} \quad (1-14)$$

where

$$H = \text{field intensity, } \frac{\text{At}}{\text{m}}$$

$$NI = \text{ampere-turns (At)}$$

$$L = \text{length between poles of coil (m)}$$

$$F_M = \text{Magnetomotive force (mmf)}$$

Example 1: Find field intensity of an 80 turn, 20 cm coil, with 6A of current.

Solution:

$$N = 80, I = 6\text{A, and } NI = 480 \text{ At}$$

$$H = \frac{480 \text{ At}}{0.2 \text{ m}} = \frac{2400 \text{ At}}{\text{m}}$$

Example 2: If the same coil in Example 1 were to be stretched to 40 cm with wire length and current remaining the same, find the new value of field intensity.

Solution:

$$N = 80, I = 6\text{A, and } NI = 480 \text{ At}$$

$$H = \frac{480 \text{ At}}{0.4 \text{ m}} = \frac{1200 \text{ At}}{\text{m}}$$

Example 3: The 20 cm coil used in Example 1 with the same current is now wound around an iron core 40 cm in length. Find the field intensity.

Solution:

$$N = 80, I = 6A, \text{ and } NI = 480 \text{ At}$$

$$H = \frac{480 \text{ At}}{0.4 \text{ m}} = \frac{1200 \text{ At}}{\text{m}}$$

Note that field intensity for Examples 2 and 3 is the same.

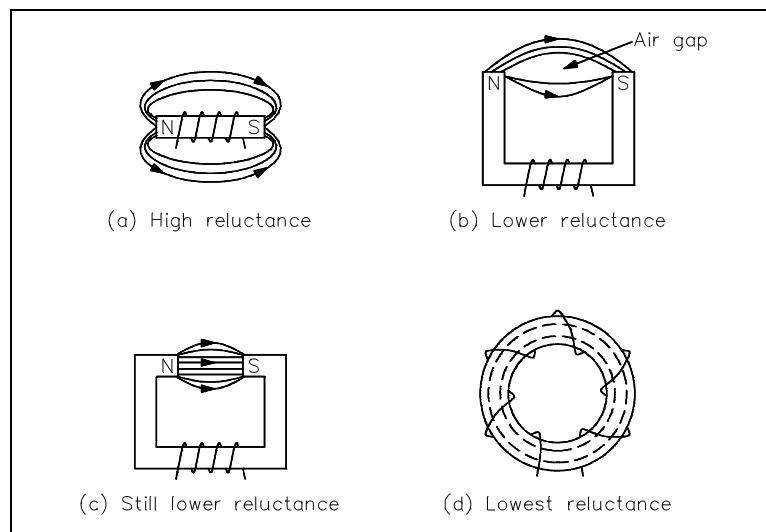


Figure 25 Different Physical Forms of Electromagnets

Reluctance

Opposition to the production of flux in a material is called *reluctance*, which corresponds to resistance. The symbol for reluctance is R , and it has the units of ampere-turns per weber (At/wb).

Reluctance is related to magnetomotive force, mmf, and flux, Φ , by the relationship shown in equation (1-15).

$$R = \frac{\text{mmf}}{\Phi} \quad (1-15)$$

Reluctance is inversely proportional to permeability (μ). Iron cores have high permeability and, therefore, low reluctance. Air has a low permeability and, therefore, a high reluctance.

Generally, different types of materials have different values of reluctance (Figure 25). Air gap is the air space between two poles of a magnet. Since air has a very high reluctance, the size of the air gap affects the value of reluctance: the shorter the air gap, the stronger the field in the gap. Air is nonmagnetic and will not concentrate magnetic lines. The larger air gap only provides space for the magnetic lines to spread out.

Summary

The important information contained in this chapter is summarized below.

Magnetism Summary

- Magnetic flux - group of magnetic field lines that are emitted outward from the north pole of a magnet
- Magnetic flux density - amount of magnetic flux per unit area of a section, perpendicular to the direction of the flux
- Weber - measure of magnetic flux
- Permeability - ability of a material to concentrate magnetic lines of flux
- Ferromagnetic materials - iron, steel, nickel, cobalt, and commercial alloys with relative permeability ranging from 50-200
- Paramagnetic materials - aluminum, platinum, manganese, and chromium with relative permeability of slightly more than one
- Diamagnetic materials - bismuth, antimony, copper, zinc, mercury, gold, and silver with relative permeability of less than one
- Magnetomotive force (mmf) - strength of a magnetic field in a coil of wire dependent on current flowing through coil
- Ampere turns - current flowing through a coil times the number of turns in the coil
- Field intensity - identifies the magnetic flux density per unit length of a coil
- Reluctance - opposition to the production of flux in a material

MAGNETIC CIRCUITS

What is a magnetic circuit? To better understand magnetic circuits, a basic understanding of the physical qualities of magnetic circuits will be necessary.

EO 1.8 EXPLAIN the physical qualities of a simple magnetic circuit, including relationships of qualities and units of measurements.

EO 1.9 Given the physical qualities of a simple magnetic circuit, CALCULATE the unknown values.

EO 1.10 DESCRIBE the shape and components of a BH magnetization curve.

EO 1.11 EXPLAIN the cause of hysteresis losses.

EO 1.12 Given Faraday's Law of induced voltage:
 a. DESCRIBE how varying parameters affect induced voltage.
 b. CALCULATE voltage induced in a conductor moving through a magnetic field.

EO 1.13 STATE Lenz's Law of induction.

Magnetic Circuits

A magnetic circuit can be compared with an electric current in which EMF, or voltage, produces a current flow. The ampere-turns (NI), or the magnetomotive force (F_m or mmf), will produce a magnetic flux Φ (Figure 26). The mmf can be compared with EMF, and the flux (Φ) can be compared to current. Equation (1-16) is the mathematical representation of magnetomotive force derived using Ohm's Law, $I = \frac{E}{R}$.

$$\Phi = \frac{F_m}{R} = \frac{\text{mmf}}{R} \quad (1-16)$$

where

Φ = magnetic flux, Wb

F_m = magnetomotive force (mmf), At

R = reluctance, $\frac{\text{At}}{\text{Wb}}$

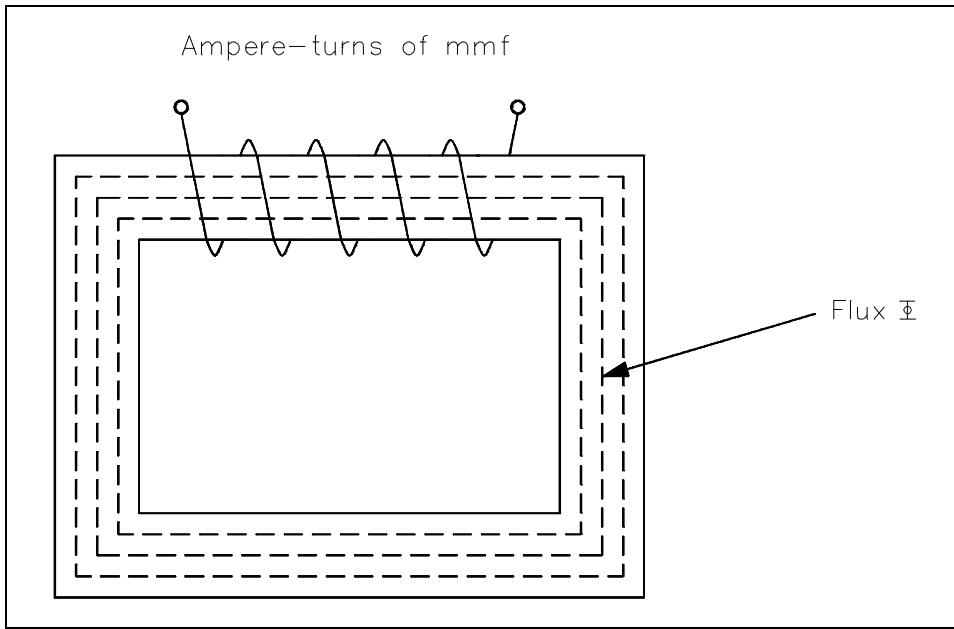


Figure 26 Magnetic Current with Closed Iron Path

Equation (1-17) is the mathematical representation for reluctance.

$$R = \frac{L}{\mu A} \quad (1-17)$$

where

$$R = \text{reluctance, } \frac{\text{At}}{\text{Wb}}$$

$$L = \text{length of coil, m}$$

$$\mu = \text{permeability of magnetic material, } \frac{(\text{T-m})}{\text{At}}$$

$$A = \text{cross-sectional area of coil, m}^2$$

Example: A coil has an mmf of 600 At, and a reluctance of 3×10^6 At/Wb. Find the total flux Φ .

Solution:

$$\Phi = \frac{\text{mmf}}{R}$$

$$\Phi = \frac{600 \text{ At}}{3 \times 10^6 \text{ At/Wb}} = 200 \times 10^{-6} \text{ Wb} = 200 \mu\text{Wb}$$

BH Magnetization Curve

The BH Magnetization Curve (Figure 27) shows how much flux density (B) results from increasing the flux intensity (H). The curves in Figure 27 are for two types of soft iron cores plotted for typical values. The curve for soft iron 1 shows that flux density B increases rapidly with an increase in flux intensity H, before the core saturates, or develops a "knee." Thereafter, an increase in flux intensity H has little or no effect on flux density B. Soft iron 2 needs a much larger increase in flux intensity H before it reaches its saturation level at $H = 5000$ At/m, $B = 0.3$ T.

Air, which is nonmagnetic, has a very low BH profile, as shown in Figure 27.

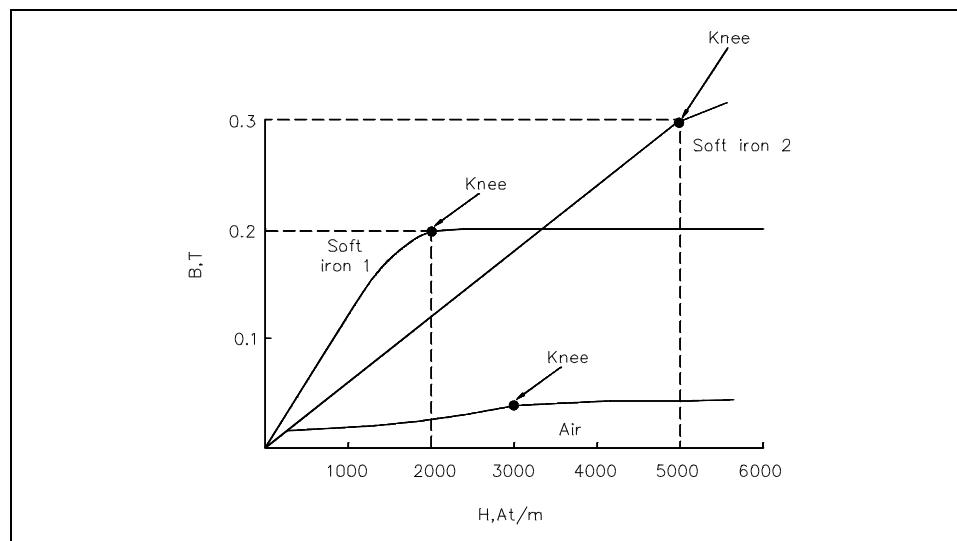


Figure 27 Typical BH Curve for Two Types of Soft Iron

The permeability (μ) of a magnetic material is the ratio of B to H . Equation (1-18) is the mathematical representation for magnetic material permeability.

$$\mu = \frac{B}{H} \quad (1-18)$$

The average value of permeability is measured where the saturation point, or knee, is first established. Figure 27 shows that the normal or average permeability for the two irons as follows.

$$\mu_{\text{soft iron 1}} = \frac{B}{H} = \frac{0.2}{2000} = 1 \times 10^{-4} \frac{(\text{T m})}{\text{At}}$$

$$\mu_{\text{soft iron 2}} = \frac{B}{H} = \frac{0.3}{5000} = 6 \times 10^{-5} \frac{(\text{T m})}{\text{At}}$$

In SI units, the permeability of a vacuum is $\mu_0 = 4 \pi \times 10^{-7} \text{ H/m}$ or 1.26×10^{-6} or T-m/At . In order to calculate permeability, the value of relative permeability μ_r must be multiplied by μ_0 . Equation (1-18) is the mathematical representation for permeability.

$$\mu = \mu_r \times \mu_0 \quad (1-18)$$

Example: Find the permeability of a material that has a relative permeability of 100.

$$\mu = \mu_r \times \mu_0 = 100 (1.26 \times 10^{-6})$$

$$= 126 \times 10^{-6} \frac{(\text{T-m})}{\text{At}}$$

Hysteresis

When current in a coil reverses direction thousands of times per second, hysteresis can cause considerable loss of energy. *Hysteresis* is defined as "a lagging behind." The magnetic flux in an iron core lags behind the magnetizing force.

The hysteresis loop is a series of curves that shows the characteristics of a magnetic material (Figure 28). Opposite directions of current will result in opposite directions of flux intensity shown as $+H$ and $-H$. Opposite polarities are also shown for flux density as $+B$ or $-B$. Current starts at the center (zero) when unmagnetized. Positive H values increase B to the saturation point, or $+B_{max}$, as shown by the dashed line. Then H decreases to zero, but B drops to the value of B_r due to hysteresis. By reversing the original current, H now becomes negative. B drops to zero and continues on to $-B_{max}$. As the $-H$ values decrease (less negative), B is reduced to $-B_r$ when H is zero. With a positive swing of current, H once again becomes positive, producing saturation at $+B_{max}$. The hysteresis loop is completed. The loop does not return to zero because of hysteresis.

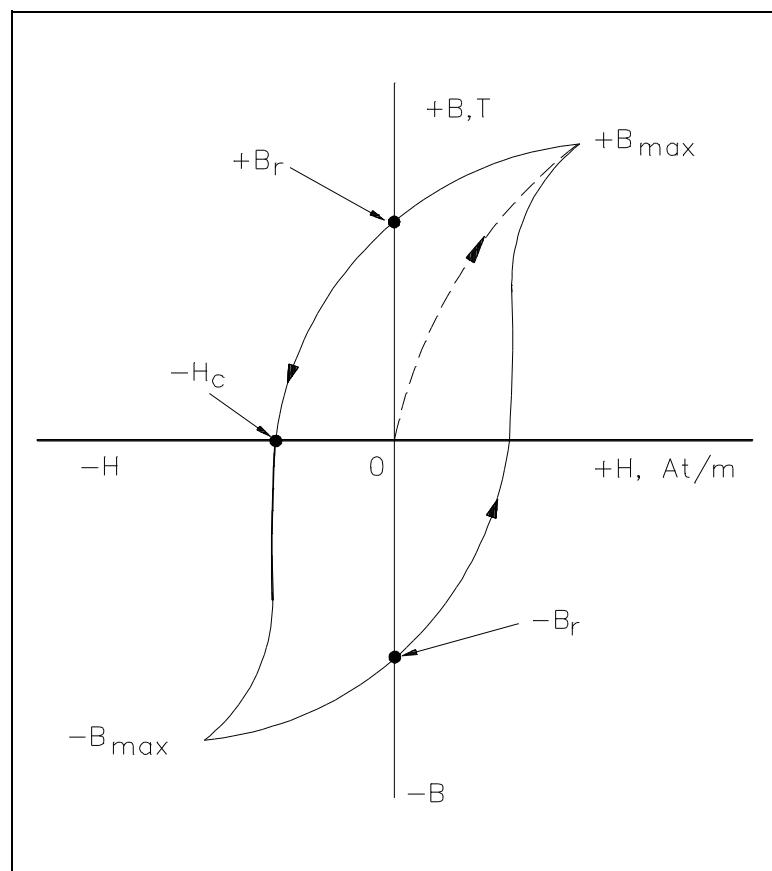


Figure 28 Hysteresis Loop for Magnetic Materials

The value of $+B_r$ or $-B_r$, which is the flux density remaining after the magnetizing force is zero, is called the *retentivity* of that magnetic material. The value of $-H_c$, which is the force that must be applied in the reverse direction to reduce flux density to zero, is called the *coercive force* of the material.

The greater the area inside the hysteresis loop, the larger the hysteresis losses.

Magnetic Induction

Electromagnetic induction was discovered by Michael Faraday in 1831. Faraday found that if a conductor "cuts across" lines of magnetic force, or if magnetic lines of force cut across a conductor, a voltage, or EMF, is induced into the conductor. Consider a magnet with its lines of force from the North Pole to the South Pole (Figure 29). A conductor C, which can be moved between the poles of the magnet, is connected to a galvanometer G, which can detect the presence of voltage, or EMF. When the conductor is not moving, zero EMF is indicated by the galvanometer.

If the conductor is moving outside the magnetic field at position 1, zero EMF is still indicated by the galvanometer. When the conductor is moved to position 2, the lines of magnetic force will be cut by the conductor, and the galvanometer will deflect to point A. Moving the conductor to position 3 will cause the galvanometer to return to zero. By reversing the direction in which the conductor is moved (3 to 1), the same results are noticed, but of opposite polarity. If we hold the conductor stationary in the magnetic lines of force, at position 2, the galvanometer indicates zero. This fact shows that there must be relative motion between the conductor and the magnetic lines of force in order to induce an EMF.

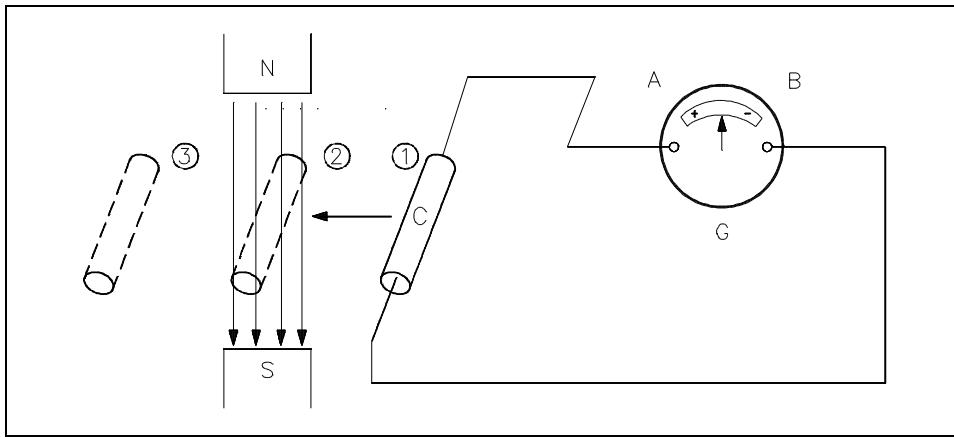


Figure 29 Induced EMF

The most important application of relative motion is seen in electric generators. In a DC generator, electromagnets are arranged in a cylindrical housing. Conductors, in the form of coils, are rotated on a core such that the coils continually cut the magnetic lines of force. The result is a voltage induced in each of the conductors. These conductors are connected in series, and the induced voltages are added together to produce the generator's output voltage.

Faraday's Law of Induced Voltage

The magnitude of the induced voltage depends on two factors: (1) the number of turns of a coil, and (2) how fast the conductor cuts across the magnetic lines of force, or flux. Equation (1-20) is the mathematical representation for Faraday's Law of Induced Voltage.

$$V_{\text{ind}} = -N \left(\frac{\Delta \Phi}{\Delta t} \right) \quad (1-20)$$

where

V_{ind} = induced voltage, V

N = number of turns in a coil

$\frac{\Delta\Phi}{\Delta t}$ = rate at which the flux cuts across the conductor, $\frac{\text{Wb}}{\text{s}}$

Example 1: Given: Flux = 4 Wb. The flux increases uniformly to 8 Wb in a period of 2 seconds. Find induced voltage in a coil that has 12 turns, if the coil is stationary in the magnetic field.

Solution:

$$V_{\text{ind}} = -N \left(\frac{\Delta\Phi}{\Delta t} \right)$$

$$\Delta\Phi = 8\text{Wb} - 4\text{Wb} = 4\text{Wb}$$

$$\Delta t = 2\text{s}$$

then

$$\frac{\Delta\Phi}{\Delta t} = \frac{4\text{Wb}}{2\text{s}} = \frac{2\text{Wb}}{\text{s}}$$

$$V_{\text{ind}} = -12 (2) = -24 \text{ volts}$$

Example 2: In Example 1, what is the induced voltage, if the flux remains 4 Wb after 2 s?

Solution:

$$V_{\text{ind}} = -12 \left(\frac{0}{2} \right) = 0 \text{ Volts}$$

No voltage is induced in Example 2. This confirms the principle that relative motion must exist between the conductor and the flux in order to induce a voltage.

Lenz's Law

Lenz's Law determines the polarity of the induced voltage. Induced voltage has a polarity that will oppose the change causing the induction. When current flows due to the induced voltage, a magnetic field is set up around that conductor so that the conductor's magnetic field reacts with the external magnetic field. This produces the induced voltage to oppose the change in the external magnetic field. The negative sign in equation (1-20) is an indication that the emf is in such a direction as to produce a current whose flux, if added to the original flux, would reduce the magnitude of the emf.

Summary

The important information contained in this chapter is summarized below.

Magnetic Circuits Summary

Simple magnetic circuit magnetic flux (Φ) is proportional to the magnetomotive force (F_m) and indirectly proportional to the reluctance (R) in a circuit.

$$\Phi \text{ (Wb)} = \frac{F_m \text{ (At)}}{R \left(\frac{\text{At}}{\text{Wb}} \right)}$$

A BH magnetization curve shows how much magnetic flux density (B) results from increasing magnetic flux intensity. The "knee" identifies the point where increasing flux intensity (H) results in a minimal increase in flux density (B).

Hysteresis losses are caused by reversing current direction thousands of times in a coil.

Faraday's Law of Induced Voltage depends on the number of turns of a coil and how fast the conductor cuts across the magnetic lines of force or flux.

$$V_{\text{ind}} = -N \frac{\Delta\Phi}{\Delta t}$$

Lenz's Law states that an induced voltage will have a polarity that will oppose the magnetic field that caused the induced voltage.

ELECTRICAL SYMBOLS

To read and interpret electrical system diagrams and schematics, one must be thoroughly familiar with the many symbols used. Once these symbols are mastered, most electrical diagrams and schematics will be understood with relative ease.

EO 1.14 Given a standard electrical symbol, IDENTIFY the component that the symbol represents. The symbols will be for the following components:

a.	Resistor	m.	Fuse
b.	Capacitor	n.	Junction
c.	Inductor	o.	AC voltage source
d.	Relay	p.	Voltmeter
e.	Contacts	q.	Ammeter
f.	Breaker	r.	Wattmeter
g.	Switch	s.	Relay operated contacts
h.	Transistor	t.	Potential transformer
i.	Rheostat	u.	Current transformer
j.	Diode	v.	Wye (Y) connection
k.	Ground connections	w.	Delta (Δ) connection
l.	Vacuum tube	x.	Light bulb
		y.	Battery

Symbols

The symbols for the various electrical components that will appear on electrical diagrams and schematics are shown in Figure 30.

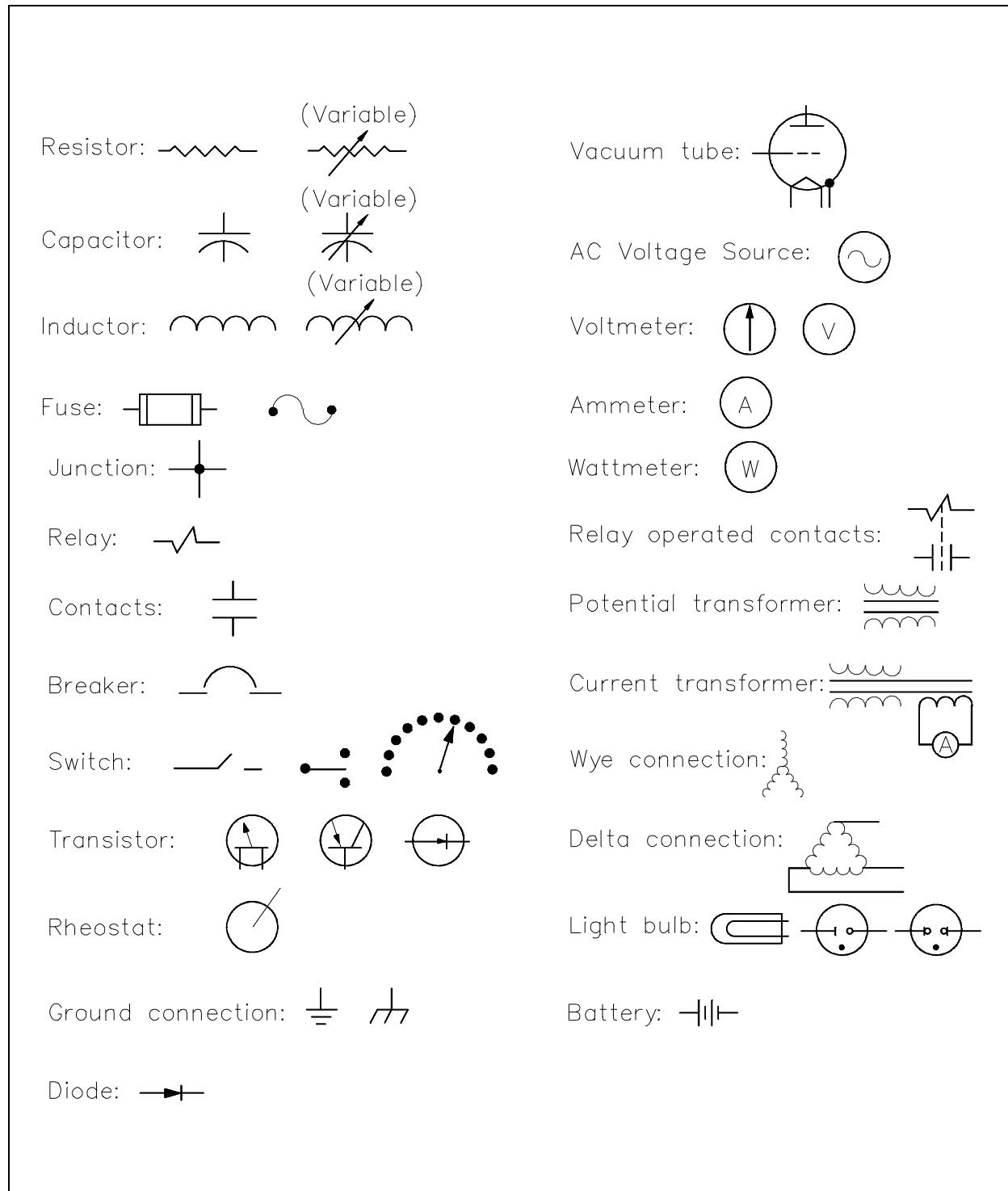


Figure 30 Electrical Symbols

Summary

The important information contained in this chapter is summarized below.

Electrical Symbols Summary

- To read and interpret electrical system diagrams and schematics, one must be thoroughly familiar with the many symbols used. Once these symbols are mastered, most electrical diagrams and schematics will be understood with relative ease.

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Appendix A
Metric System and Powers of Ten

BASIC ELECTRICAL THEORY

APPENDIX A

METRIC SYSTEM AND POWERS OF TEN

Metric System

Units of the international metric system, commonly called SI (system internationale), are used in electricity. The seven basic units are shown on Table A-1. Two supplementary units of SI are shown on Table A-2.

TABLE A-1
BASE UNITS of the
INTERNATIONAL METRIC SYSTEM

<u>Quantity</u>	<u>Base Unit</u>	<u>Symbol</u>
Length	meter	m
Mass	kilogram	Kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	Kelvin	K
Light intensity	Candela	cd
Amount of substance	mole	mol

TABLE A-2
SUPPLEMENTARY SI UNITS

<u>Quantity</u>	<u>Unit</u>	<u>Symbol</u>
Plane angle	radian	rad
Solid angle	steradian	Sr

These base and supplemental units are used to derive other units. Most of the units of measure used in electricity are derived units. These units are shown on Table A-3. Some of these are derived from the base units, and some are derived from other derived units, or a combination of both. For example, the unit of current is the ampere, which is derived from the base units of second and coulomb. The derivation of these units is beyond the scope of this text. However, units commonly used in the study and use of electricity and their relationship to other units of measure are discussed in Chapter 3, *Units of Electrical Measurement*.

TABLE A-3
DERIVED SI UNITS

<u>Quantity</u>	<u>Derived Unit</u>	<u>Symbol</u>
Energy	joule	J
Force	newton	N
Power	watt	W
Electric charge	coulomb	C
Electric potential	volt	V
Electric resistance	ohm	Ω
Electric conductance	mho	\mathcal{O}
Electric capacitance	farad	F
Electric inductance	henry	H
Frequency	hertz	Hz
Magnetic flux	weber	Wb
Magnetic flux density	tesla	T

Metric Prefixes

When working with basic electrical measurement units, sometimes the values are too large or too small to express conveniently. For convenience, add metric prefixes (Table A-4) to the basic unit. For example, if we have a resistor that is 1,000,000 ohms (Ω), we can add the prefix kilo, or its designated symbol K, and express the value as 1,000 K Ω , or the metric prefix mega (symbol M) and express the value as 1 M Ω . In the case of capacitance or current, we may have a very small value such as 0.002 amperes (symbol A) or 0.000005 farads (symbol F). These values can be expressed by adding the prefix milli (symbol m) and expressing the current as 2 milli amperes or 2 mA, or adding the prefix micro (symbol μ) and expressing the capacitance as 5 micro farads, or 5 μ F.

To use the prefixes listed in Table A-4, divide the value of the unit by the value of the prefix, and then add the prefix to the unit.

TABLE A-4
METRIC PREFIXES USED in ELECTRICITY

<u>Prefix</u> (letter symbol)		<u>Value</u>
mega (M)	million	1,000,000
kilo (k)	thousand	1,000
milli (m)	thousandth	0.001
micro (μ)	millionth	0.000,001
nano (n)	thousand-millionth	0.000,000,001
pico (p)	million-millionth	0.000,000,000,001

Powers of Ten

Another way to express large and small values is to convert the value to powers of 10. This is a convenient way to express values and keep the units in the basic unit notation, rather than converting from one unit of measure to another unit that may be larger or smaller, as we did in metric prefixes above.

Examples of expressing numbers as power of 10 are shown in Table A-5.

TABLE A-5
POWERS of 10

<u>Number = Power of 10</u>	<u>Commonly Read As</u>
$0.000,001 = 10^{-6}$	10 to the minus sixth
$0.000,01 = 10^{-5}$	10 to the minus fifth
$0.000,1 = 10^{-4}$	10 to the minus fourth
$0.001 = 10^{-3}$	10 to the minus third
$0.01 = 10^{-2}$	10 to the minus two
$0.1 = 10^{-1}$	10 to the minus one
$1 = 10^0$	10 to the zero
$10 = 10^1$	10 to the first
$100 = 10^2$	10 to the second
$1,000 = 10^3$	10 to the third
$10,000 = 10^4$	10 to the fourth
$100,000 = 10^5$	10 to the fifth
$1,000,000 = 10^6$	10 to the sixth

Rules associated with powers of ten are as follows:

Rule 1: To express numbers larger than 1 as a small number times a power of 10, move the decimal point to the left as many places as desired. Then multiply the number obtained by 10 to a power that is equal to the number of places moved.

Example: To convert 6,000,000, move the decimal point 6 places to the left (6.000,000), then multiply 6 times 10 raised to a power equal to the number of decimal places moved, obtaining 6×10^6 .

$$6,000,000 = 6 \times 10^6$$

Rule 2: To express numbers less than 1 as a whole number times a power of 10, move the decimal point to the right as many places as desired. Then multiply the number obtained by 10 to a negative power that is equal to the number of places moved.

Example: To convert 0.004A, move the decimal point 3 places to the right (004.), then multiply 4 by 10 raised to a negative power equal to the number of decimal places moved, obtaining $4 \times 10^{-3}A$.

$$0.004A = 4 \times 10^{-3}A$$

Rule 3: To convert a number expressed as a positive power of 10 to a decimal number, move the decimal point to the right as many places as the value of the exponent.

Example: To convert $1 \times 10^3\Omega$, move the decimal point 3 places to the right (1000.0), then drop the multiple of power of 10, obtaining 1,000.

$$1 \times 10^3 = 1,000\Omega$$

Rule 4: To convert a number expressed as a negative power of 10 to a decimal number, move the decimal point to the left as many places as the value of the exponent.

Example: To convert $5 \times 10^{-3} \text{A}$, move the decimal point 3 places to the left (0.005), then drop the multiple of the power of 10, obtaining 0.005A.

$$5 \times 10^{-3} \text{A} = 0.005 \text{A}$$

Rule 5: To multiply 2 or more numbers expressed as powers of 10, multiply the coefficients to obtain the new coefficient, and add the exponents to obtain the new exponent of 10.

Example: To multiply 2×10^5 by 3×10^{-3} , multiply 2×3 to get 6, then add the exponents of the powers of 10, $5 + (-3)$, to get an exponent of 2, obtaining a product of 6×10^2 .

$$(2 \times 10^5) (3 \times 10^{-3}) = 6 \times 10^2$$

Rule 6: To divide powers of 10, use the formula:

$$\frac{1}{10^n} = 1 \times 10^{-n}$$

We can transfer any power of 10 from numerator to denominator, or vice-versa, simply by changing the sign of the exponent.

Example: To divide 8×10^{-5} by 2×10^{-4} , divide the numerical number 8 by 2 = 4, then bring the power of 10, in the denominator, up to the numerator and change the sign of its exponent, then add the exponents together:

$$\frac{8 \times 10^{-5}}{2 \times 10^{-4}} = 4 \times 10^{-5+4} = 4 \times 10^{-1}$$

Table A-6 shows the metric prefixes expressed as powers of 10.

TABLE A-6
METRIC PREFIXES EXPRESSED
as POWERS of 10

Metric Prefix Power of 10

mega (M)	10^6
kilo (k)	10^3
milli (m)	10^{-3}
micro (μ)	10^{-6}
nano (n)	10^{-9}
pico (p)	10^{-12}

Electrical units can be expressed in different, but equivalent, units by using prefixes expressed in powers of 10.

Examples:

Express 780,000 Ω in Megohms ($M\Omega$).

$$1\Omega = 10^{-6} M\Omega$$

$$780,000 \Omega = 780,000 \Omega \times 10^{-6} = 0.78 M\Omega$$

Express 4.5 V in millivolts (mV).

$$1 V = 10^3 mV$$

$$4.5 V = 4.5 \times 10^3 mV = 4500 mV$$

Express 0.015 A in milliamperes (mA).

$$1 \text{ A} = 10^3 \text{ mA}$$

$$0.015 \text{ A} = 0.015 \times 10^3 = 15 \text{ mA}$$

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**Department of Energy
Fundamentals Handbook**

**ELECTRICAL SCIENCE
Module 2
Basic DC Theory**

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REFERENCES

- Gussow, Milton, Schaum's Outline Series, Basic Electricity, McGraw-Hill.
- Academic Program for Nuclear Power Plant Personnel, Volume IV, Columbia, MD: General Physics Corporation, Library of Congress Card #A 326517, 1982.
- Sienko and Plane, Chemical Principles and Properties, 2nd Edition, McGraw-Hill.
- Academic Program for Nuclear Power Plant Personnel, Volume II, Columbia, MD: General Physics Corporation Library of Congress Card #A 326517, 1982.
- Nasar and Unnewehr, Electromechanics and Electric Machines, John Wiley and Sons.
- Van Valkenburgh, Nooger, and Neville, Basic Electricity, Vol. 5, Hayden Book Company.
- Exide Industrial Marketing Division, The Storage Battery, Lead-Acid Type, The Electric Storage Battery Company.
- Lister, Eugene C., Electric Circuits and Machines, 5th Edition, McGraw-Hill.
- Croft, Carr, Watt, and Summers, American Electricians Handbook, 10th Edition, McGraw-Hill.
- Mason, C. Russel, The Art and Science of Protective Relaying, John Wiley and Sons.
- Mileaf, Harry, Electricity One - Seven, Revised 2nd Edition, Hayden Book Company.
- Buban and Schmitt, Understanding Electricity and Electronics, 3rd Edition, McGraw-Hill.
- Kidwell, Walter, Electrical Instruments and Measurements, McGraw-Hill.

TERMINAL OBJECTIVE

1.0 Using the rules associated with basic DC circuit characteristics, **ANALYZE** various DC circuits to find resistances, currents, and voltages at any given point within the circuit.

ENABLING OBJECTIVES

1.1 **LIST** the four ways to produce a DC voltage.

1.2 **STATE** the purpose of a rectifier.

1.3 **DESCRIBE** the outputs of the following circuits:

- Half-wave bridge rectifier
- Full-wave bridge rectifier

1.4 Given a diagram, **IDENTIFY** it as one of the following types:

- Schematic diagram
- One-line diagram
- Block diagram
- Wiring diagram

1.5 **DEFINE** the following terms:

- Resistivity
- Temperature coefficient of resistance
- Closed circuit
- Open circuit
- Short circuit
- Series circuit
- Parallel circuit
- Equivalent resistance

1.6 Given a circuit, **DETERMINE** whether the circuit is an open circuit or a closed circuit.

1.7 Given a circuit, **CALCULATE** total resistance for a series or parallel circuit.

1.8 **DESCRIBE** what is meant by the term "voltage divider."

1.9 **DESCRIBE** what is meant by the term "current division."

ENABLING OBJECTIVES (Cont.)

- 1.10 **DESCRIBE** the difference between electron flow and conventional current flow.
- 1.11 Given a circuit showing current flows, **IDENTIFY** the polarity of the voltage drops in the circuit.
- 1.12 **STATE** Kirchhoff's voltage law.
- 1.13 **STATE** Kirchhoff's current law.
- 1.14 Given a circuit, **SOLVE** problems for voltage and current using Kirchhoff's laws.
- 1.15 Given a simple DC circuit, **DETERMINE** the equivalent resistance of series and parallel combinations of elements.
- 1.16 **DESCRIBE** the voltage and current effects of an open in a DC circuit.
- 1.17 **DESCRIBE** the voltage and current effects in a shorted DC circuit.

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DC SOURCES

When most people think of DC, they usually think of batteries. In addition to batteries, however, there are other devices that produce DC which are frequently used in modern technology.

- 1.1 LIST the four ways to produce a DC voltage.**
- 1.2 STATE the purpose of a rectifier.**
- 1.3 DESCRIBE the outputs of the following circuits:**
 - a. Half-wave bridge rectifier**
 - b. Full-wave bridge rectifier**

Batteries

A battery consists of two or more chemical cells connected in series. The combination of materials within a battery is used for the purpose of converting chemical energy into electrical energy. To understand how a battery works, we must first discuss the chemical cell.

The chemical cell is composed of two electrodes made of different types of metal or metallic compounds which are immersed in an electrolyte solution. The chemical actions which result are complicated, and they vary with the type of material used in cell construction. Some knowledge of the basic action of a simple cell will be helpful in understanding the operation of a chemical cell in general.

In the cell, electrolyte ionizes to produce positive and negative ions (Figure 1, Part A). Simultaneously, chemical action causes the atoms within one of the electrodes to ionize.

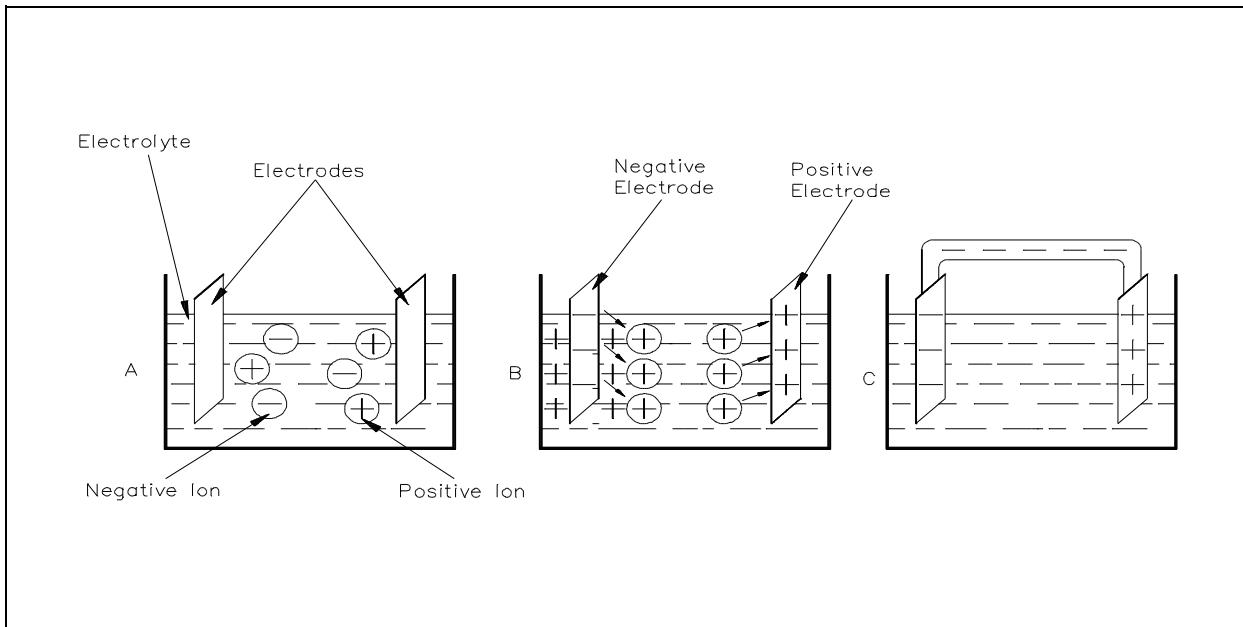


Figure 1 Basic Chemical Battery

Due to this action, electrons are deposited on the electrode, and positive ions from the electrode pass into the electrolyte solution (Part B). This causes a negative charge on the electrode and leaves a positive charge in the area near the electrode (Part C).

The positive ions, which were produced by ionization of the electrolyte, are repelled to the other electrode. At this electrode, these ions will combine with the electrons. Because this action causes removal of electrons from the electrode, it becomes positively charged.

DC Generator

A simple DC generator consists of an armature coil with a single turn of wire. The armature coil cuts across the magnetic field to produce a voltage output. As long as a complete path is present, current will flow through the circuit in the direction shown by the arrows in Figure 2. In this coil position, commutator segment 1 contacts with brush 1, while commutator segment 2 is in contact with brush 2.

Rotating the armature one-half turn in the clockwise direction causes the contacts between the commutator segments to be reversed. Now segment 1 is contacted by brush 2, and segment 2 is in contact with brush 1.

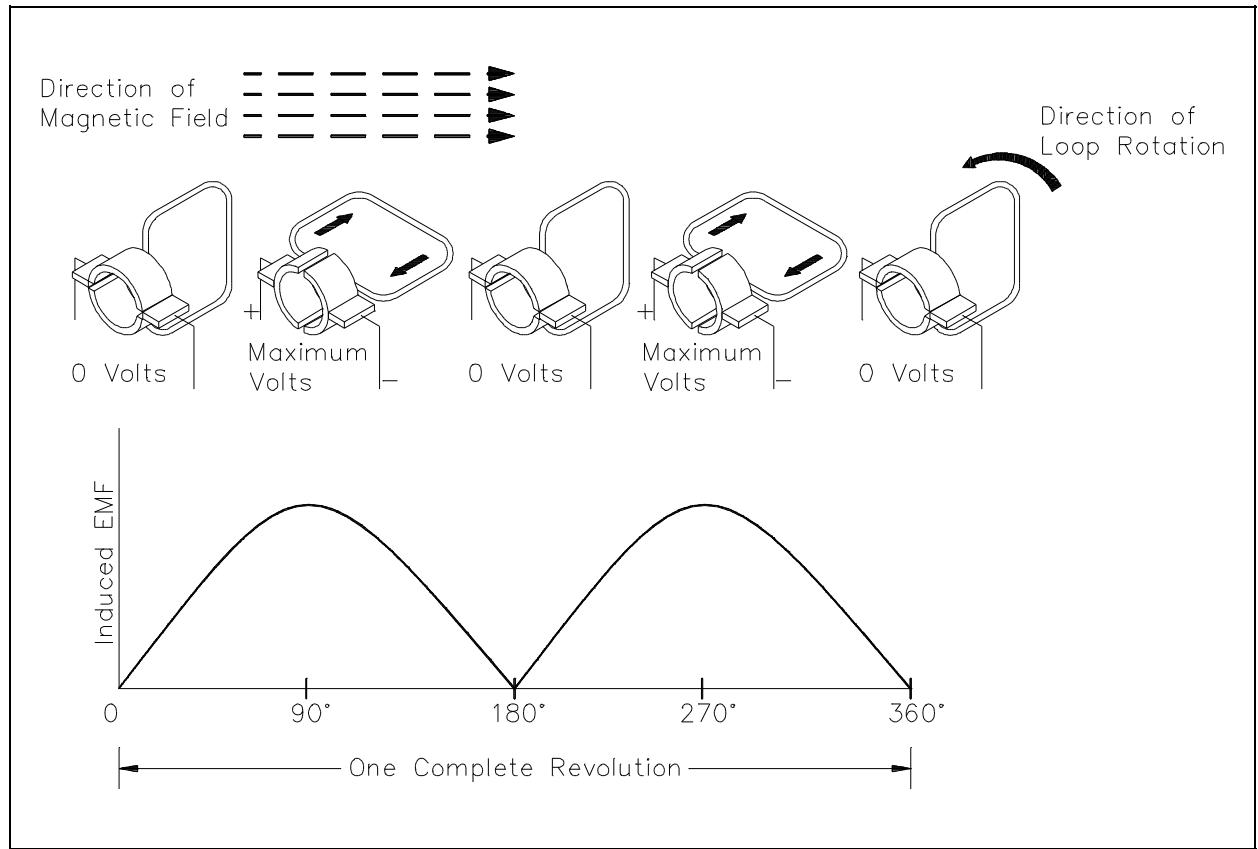


Figure 2 Basic DC Generator

Due to this commutator action, that side of the armature coil which is in contact with either of the brushes is always cutting the magnetic field in the same direction. Brushes 1 and 2 have a constant polarity, and pulsating DC is delivered to the load circuit.

Thermocouples

A thermocouple is a device used to convert heat energy into a voltage output. The thermocouple consists of two different types of metal joined at a junction (Figure 3).

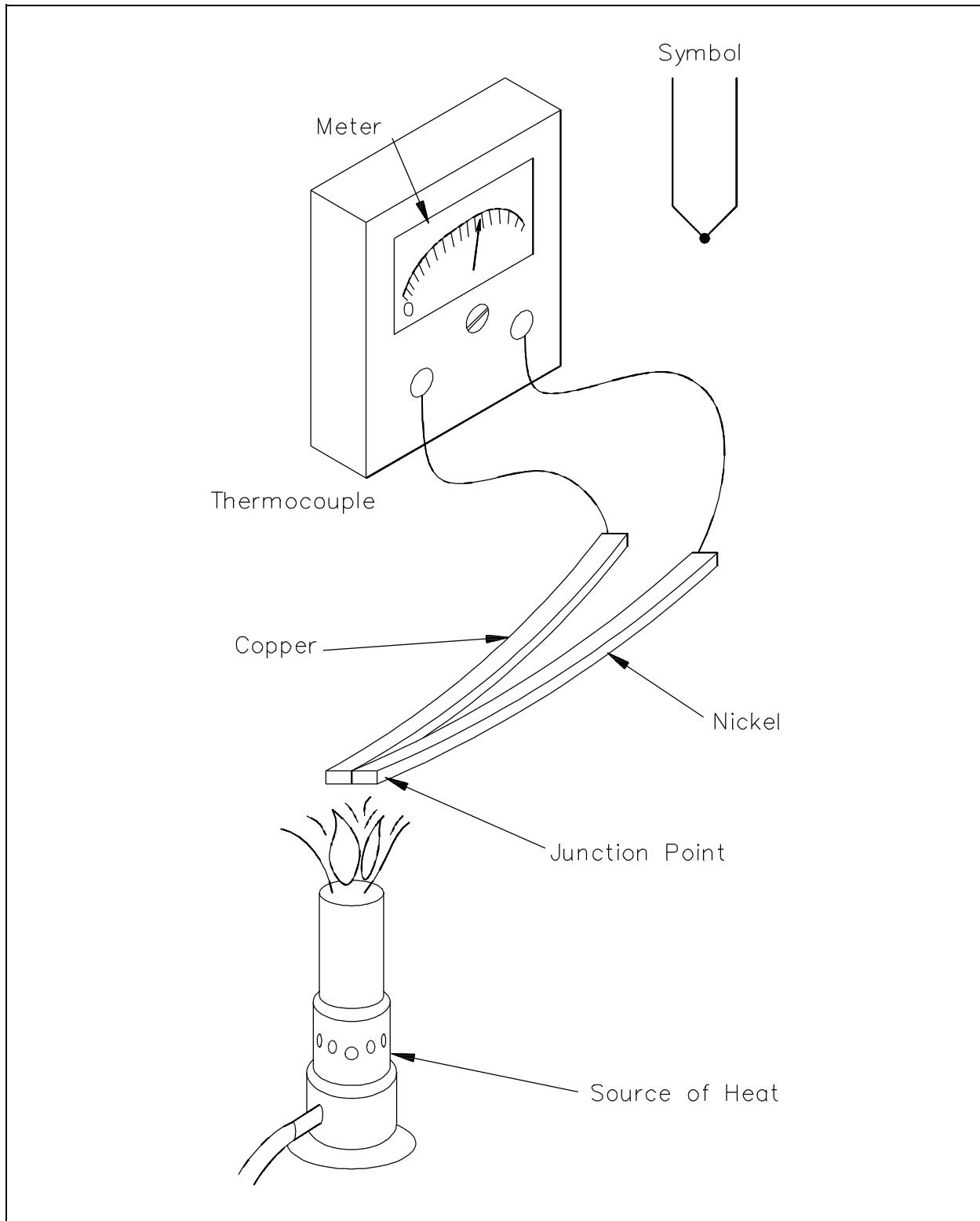


Figure 3 Production of a DC Voltage Using a Thermocouple

As the junction is heated, the electrons in one of the metals gain enough energy to become free electrons. The free electrons will then migrate across the junction and into the other metal. This displacement of electrons produces a voltage across the terminals of the thermocouple. The combinations used in the makeup of a thermocouple include: iron and constantan; copper and constantan; antimony and bismuth; and chromel and alumel.

Thermocouples are normally used to measure temperature. The voltage produced causes a current to flow through a meter, which is calibrated to indicate temperature.

Rectifiers

Most electrical power generating stations produce alternating current. The major reason for generating AC is that it can be transferred over long distances with fewer losses than DC; however, many of the devices which are used today operate only, or more efficiently, with DC. For example, transistors, electron tubes, and certain electronic control devices require DC for operation. If we are to operate these devices from ordinary AC outlet receptacles, they must be equipped with rectifier units to convert AC to DC. In order to accomplish this conversion, we use diodes in rectifier circuits. The purpose of a rectifier circuit is to convert AC power to DC.

The most common type of solid state diode rectifier is made of silicon. The diode acts as a gate, which allows current to pass in one direction and blocks current in the other direction. The polarity of the applied voltage determines if the diode will conduct. The two polarities are known as forward bias and reverse bias.

Forward Bias

A diode is forward biased when the positive terminal of a voltage source is connected to its anode, and the negative terminal is connected to the cathode (Figure 4A). The power source's positive side will tend to repel the holes in the p-type material toward the p-n junction by the negative side. A hole is a vacancy in the electron structure of a material. Holes behave as positive charges. As the holes and the electrons reach the p-n junction, some of them break through it (Figure 4B). Holes combine with electrons in the n-type material, and electrons combine with holes in the p-type material.

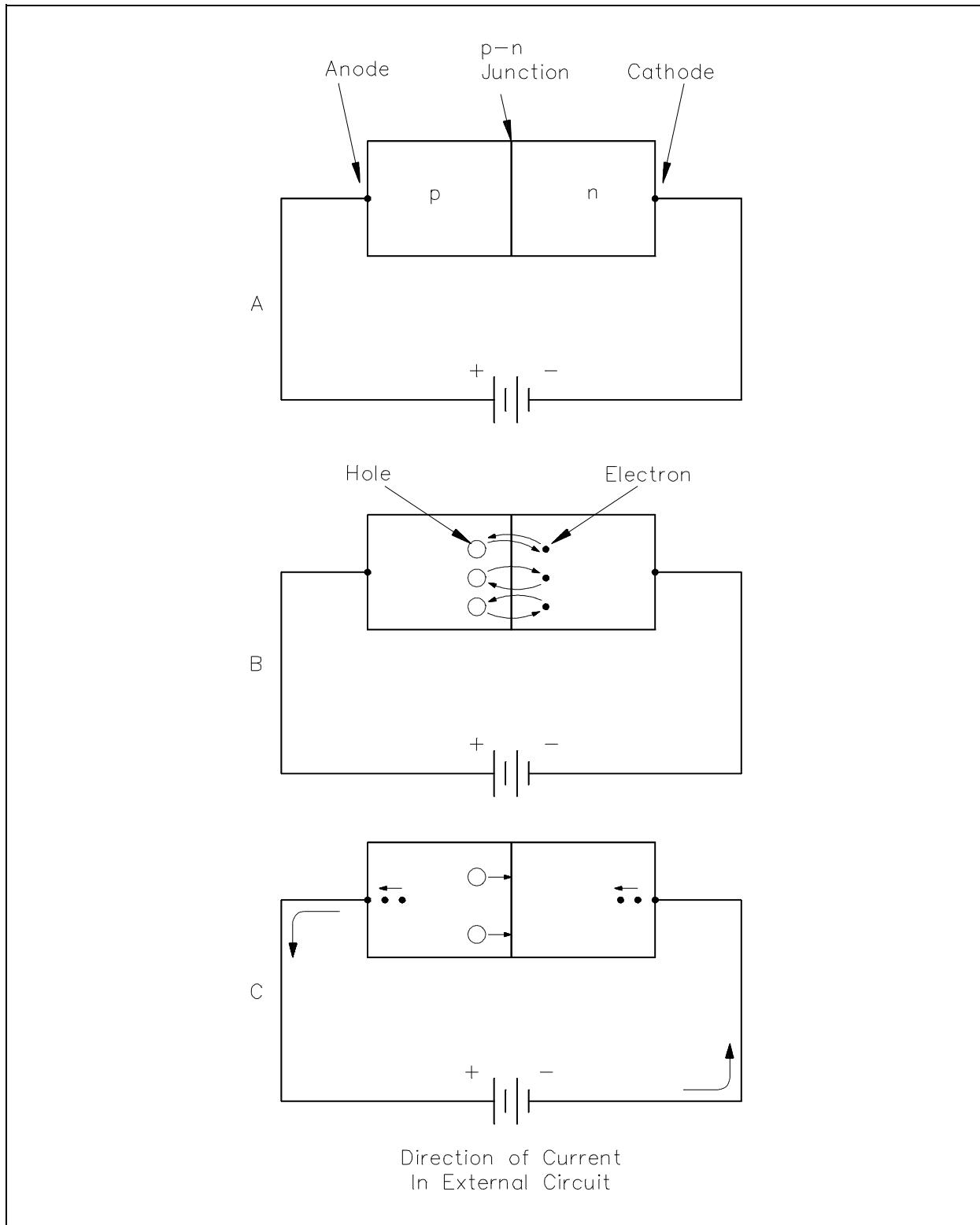


Figure 4 Forward-Biased Diode

When a hole combines with an electron, or an electron combines with a hole near the p-n junction, an electron from an electron-pair bond in the p-type material breaks its bond and enters the positive side of the source. Simultaneously, an electron from the negative side of the source enters the n-type material (Figure 4C). This produces a flow of electrons in the circuit.

Reverse Bias

Reverse biasing occurs when the diode's anode is connected to the negative side of the source, and the cathode is connected to the positive side of the source (Figure 5A). Holes within the p-type material are attracted toward the negative terminal, and the electrons in the n-type material are attracted to the positive terminal (Figure 5B). This prevents the combination of electrons and holes near the p-n junction, and therefore causes a high resistance to current flow. This resistance prevents current flow through the circuit.

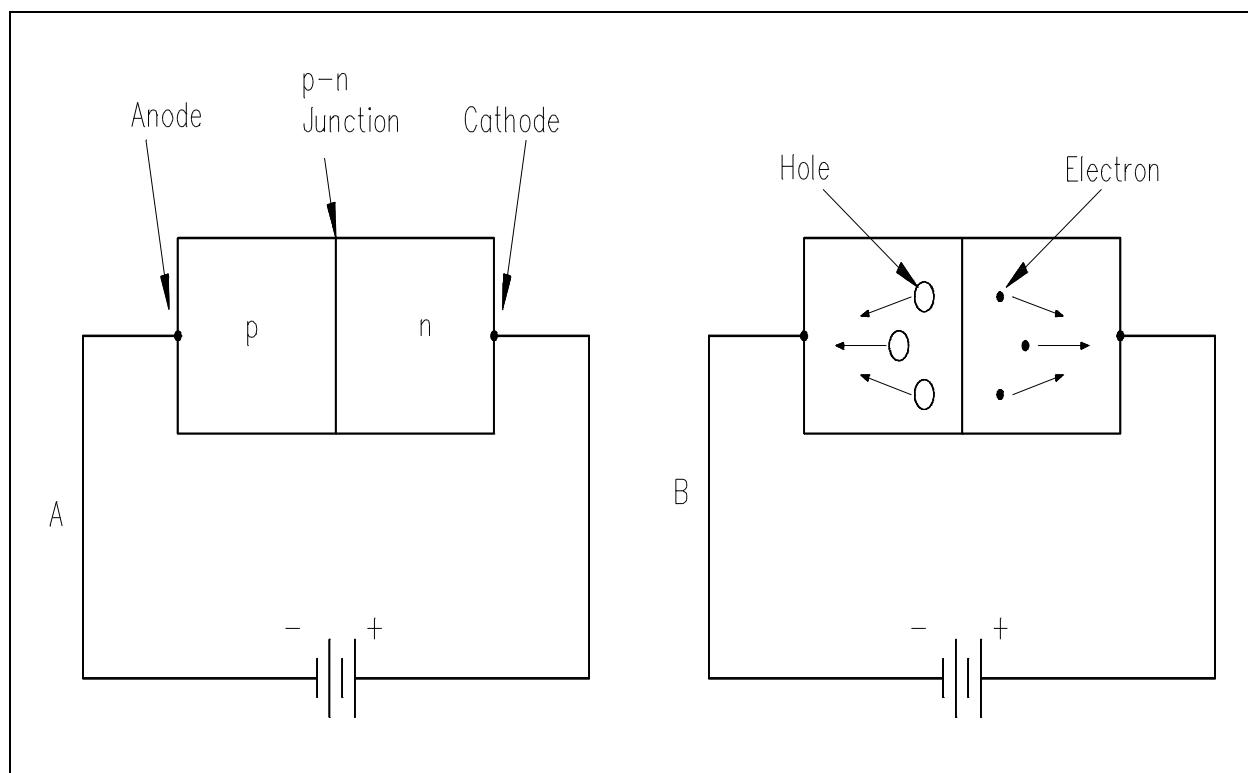


Figure 5 Reverse-Biased Diode

Half-Wave Rectifier Circuit

When a diode is connected to a source of alternating voltage, it will be alternately forward-biased, and then reverse-biased, during each cycle of the AC sine-wave. When a single diode is used in a rectifier circuit, current will flow through the circuit only during one-half of the input voltage cycle (Figure 6). For this reason, this rectifier circuit is called a half-wave rectifier. The output of a half-wave rectifier circuit is pulsating DC.

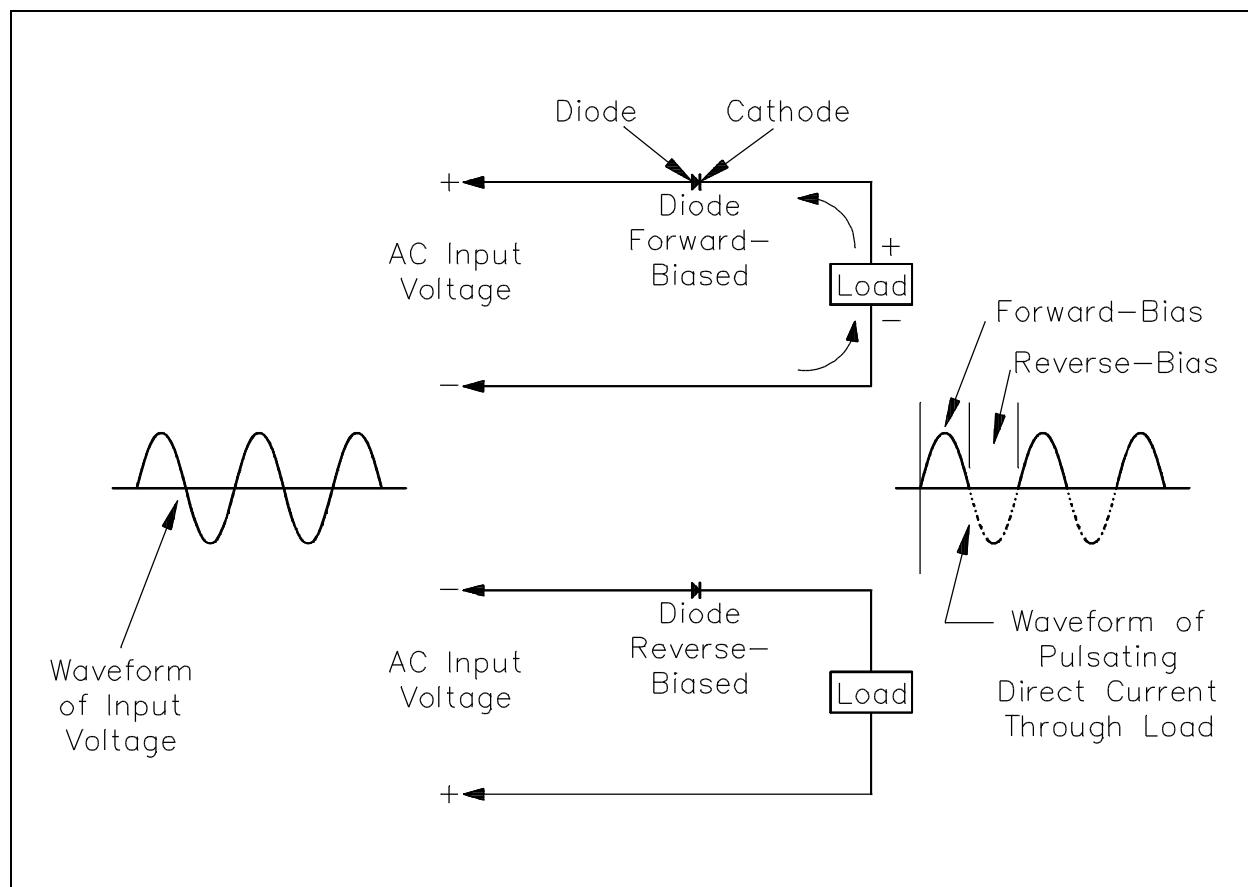


Figure 6 Half-Wave Rectifier

Full-Wave Rectifier Circuit

A full-wave rectifier circuit is a circuit that rectifies the entire cycle of the AC sine-wave. A basic full-wave rectifier uses two diodes. The action of these diodes during each half cycle is shown in Figure 7.

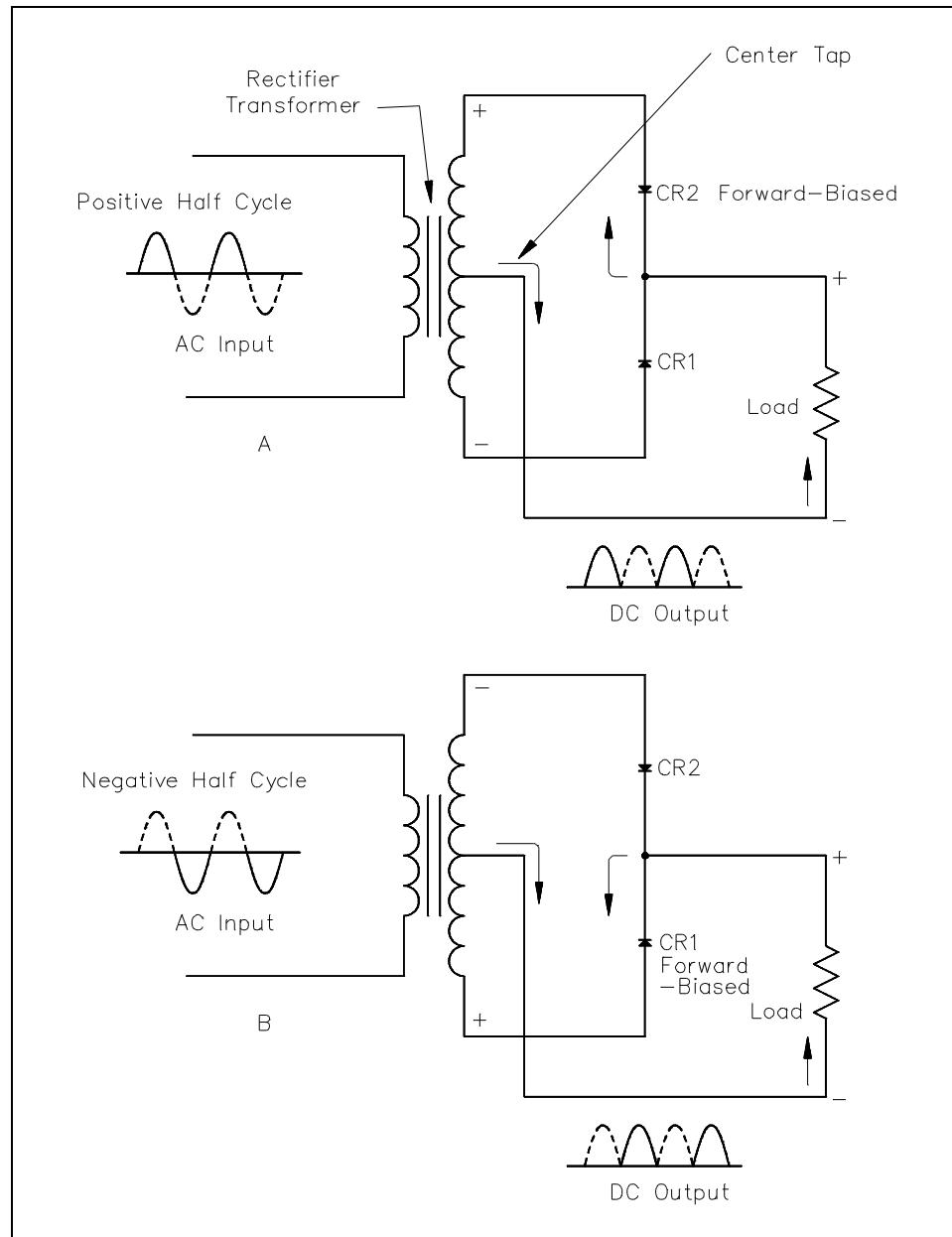


Figure 7 Full-Wave Rectifier

Another type of full-wave rectifier circuit is the full-wave bridge rectifier. This circuit utilizes four diodes. These diodes' actions during each half cycle of the applied AC input voltage are shown in Figure 8. The output of this circuit then becomes a pulsating DC, with all of the waves of the input AC being transferred. The output looks identical to that obtained from a full-wave rectifier (Figure 7).

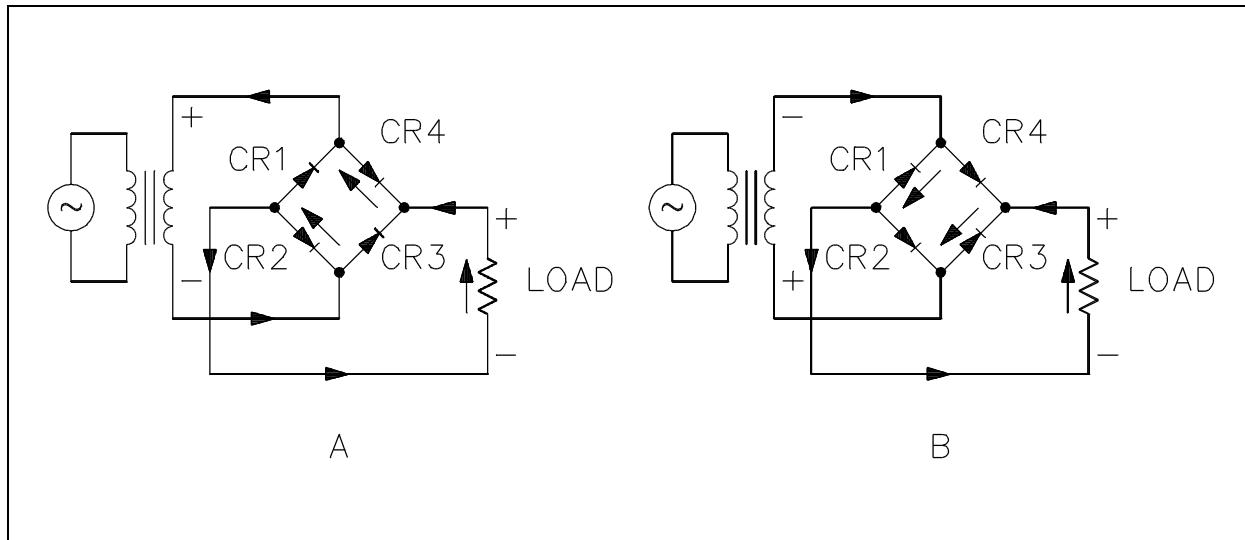


Figure 8 Bridge Rectifier Circuit

Summary

The important information concerning DC sources is summarized below.

DC Sources Summary

- There are four common ways that DC voltages are produced.
 - Batteries
 - DC Generators
 - Thermocouples
 - Rectifiers
- Thermocouples convert energy from temperature into a DC voltage. This voltage can be used to measure temperature.
- A rectifier converts AC to DC.
- There are two types of rectifiers.
 - Half-Wave rectifiers
 - Full-Wave rectifiers
- Half-wave rectifiers convert the AC to a pulsating DC and convert only one-half of the sine wave.
- Full-wave rectifiers convert the AC to a pulsating DC and convert all of the sine wave.

DC CIRCUIT TERMINOLOGY

Before operations with DC circuits can be studied, an understanding of the types of circuits and common circuit terminology associated with circuits is essential.

EO 1.4 Given a diagram, IDENTIFY it as one of the following types:

- a. Schematic diagram
- b. One-line diagram
- c. Block diagram
- d. Wiring diagram

EO 1.5 DEFINE the following terms:

- a. Resistivity
- b. Temperature coefficient of resistance
- c. Closed circuit
- d. Open circuit
- e. Short circuit
- f. Series circuit
- g. Parallel circuit
- h. Equivalent resistance

EO 1.6 Given a circuit, DETERMINE whether the circuit is an open circuit or a closed circuit.

Schematic Diagram

Schematic diagrams are the standard means by which we communicate information in electrical and electronics circuits. On schematic diagrams, the component parts are represented by graphic symbols, some of which were presented earlier in Module 1. Because graphic symbols are small, it is possible to have diagrams in a compact form. The symbols and associated lines show how circuit components are connected and the relationship of those components with one another.

As an example, let us look at a schematic diagram of a two-transistor radio circuit (Figure 9). This diagram, from left to right, shows the components in the order they are used to convert radio waves into sound energy. By using this diagram it is possible to trace the operation of the circuit from beginning to end. Due to this important feature of schematic diagrams, they are widely used in construction, maintenance, and servicing of all types of electronic circuits.

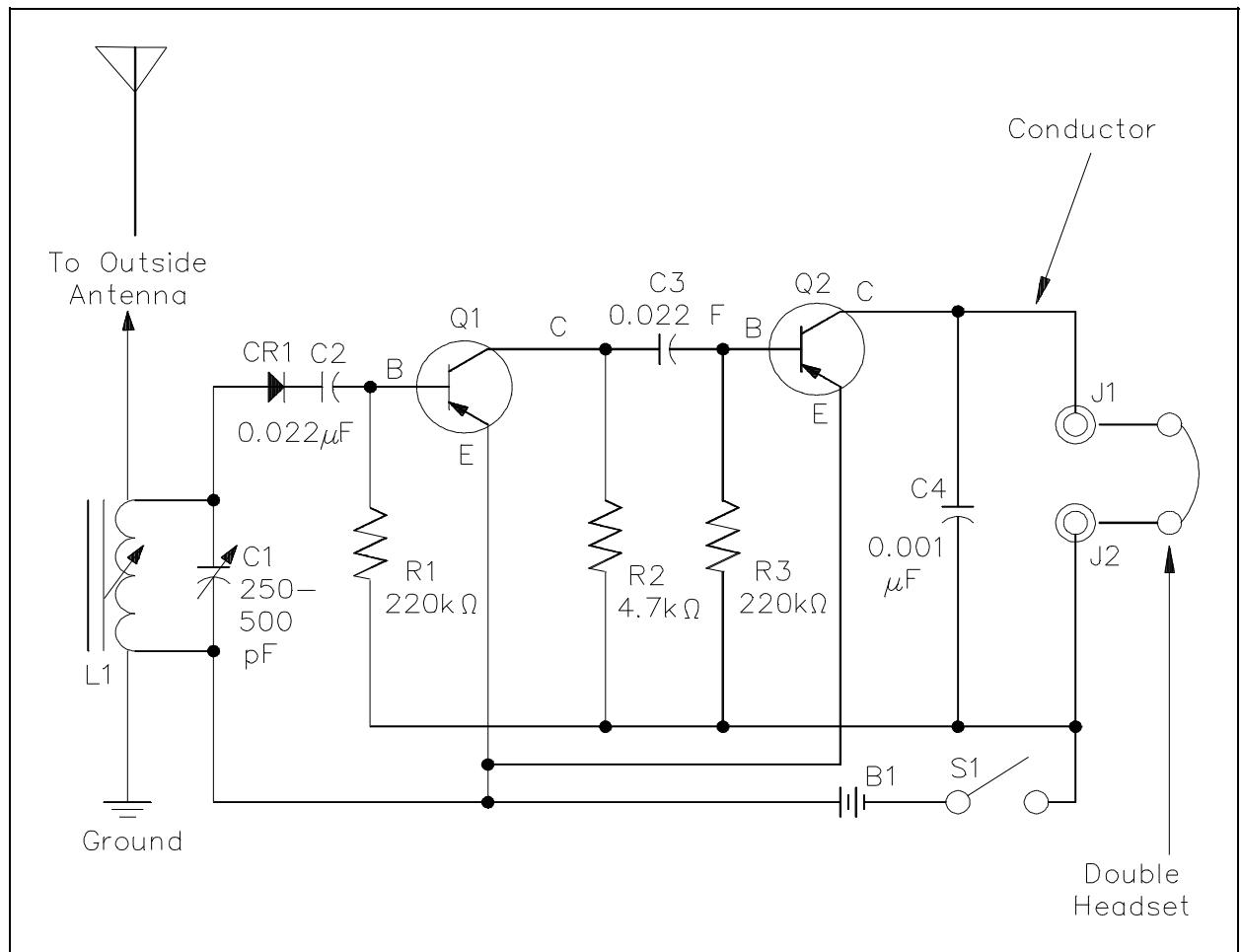


Figure 9 Schematic Diagram

One-Line Diagram

The one-line, or single-line, diagram shows the components of a circuit by means of single lines and the appropriate graphic symbols. One-line diagrams show two or more conductors that are connected between components in the actual circuit. The one-line diagram shows all pertinent information about the sequence of the circuit, but does not give as much detail as a schematic diagram. Normally, the one-line diagram is used to show highly complex systems without showing the actual physical connections between components and individual conductors.

As an example, Figure 10 shows a typical one-line diagram of an electrical substation.

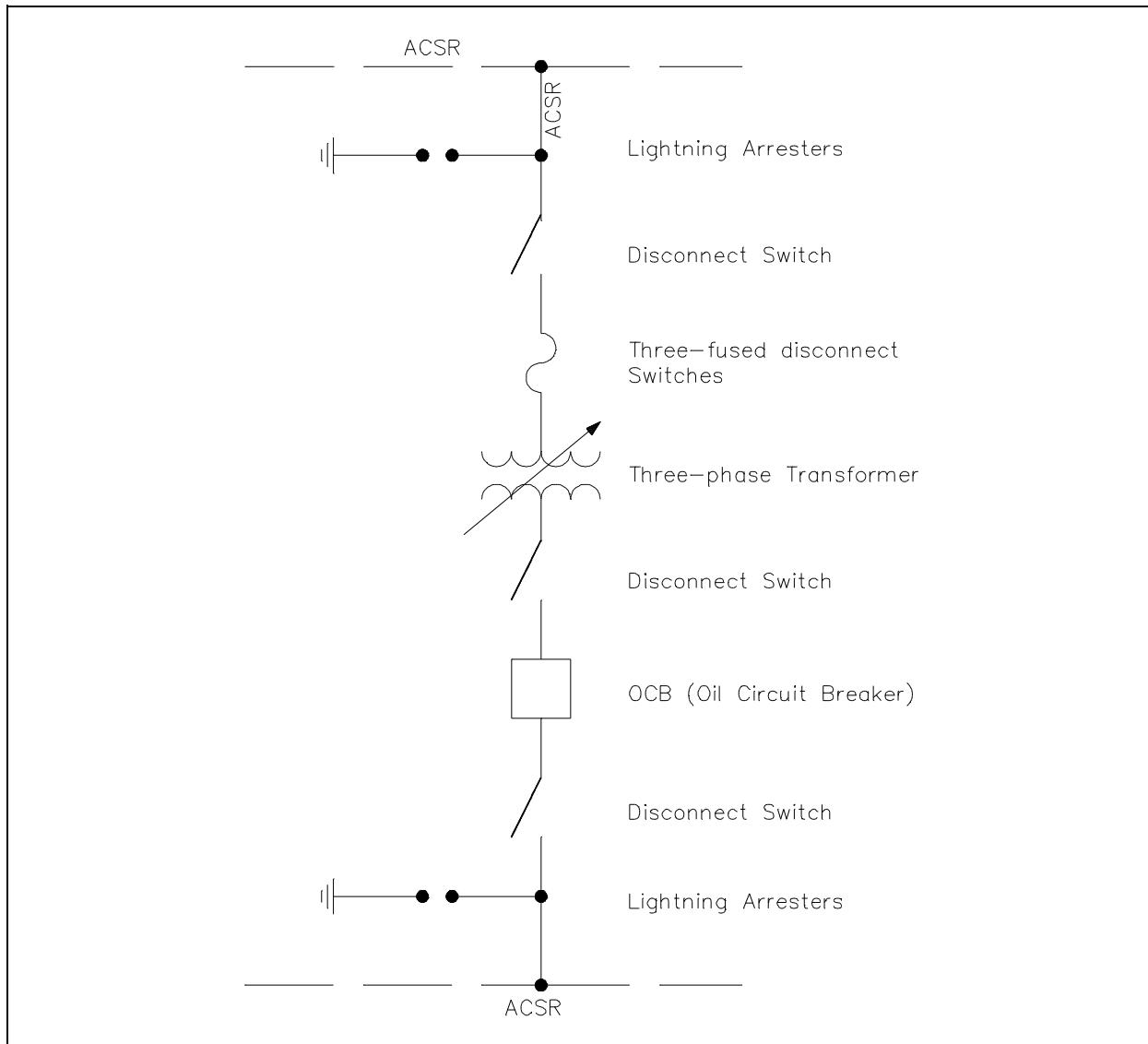


Figure 10 One-Line Diagram

Block Diagram

A block diagram is used to show the relationship between component groups, or stages in a circuit. In block form, it shows the path through a circuit from input to output (Figure 11). The blocks are drawn in the form of squares or rectangles connected by single lines with arrowheads at the terminal end, showing the direction of the signal path from input to output. Normally, the necessary information to describe the stages of components is contained in the blocks.

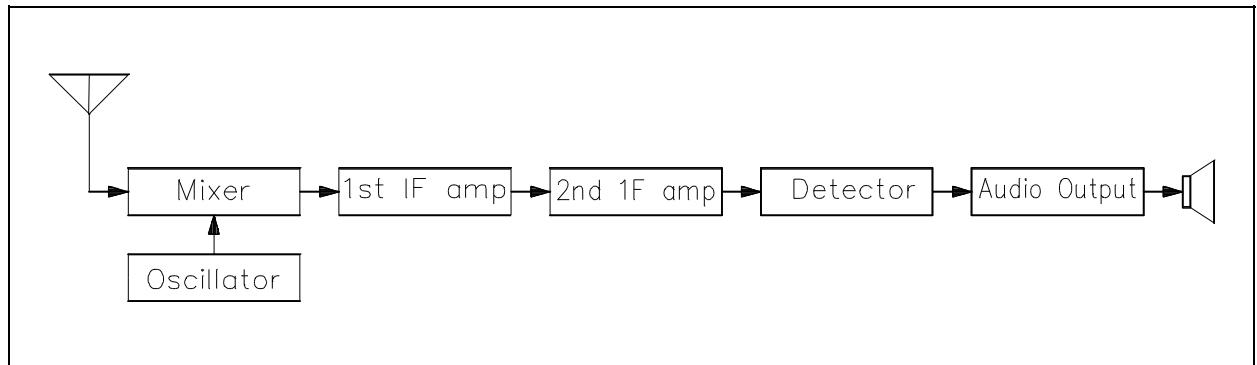


Figure 11 Block Diagram

Wiring Diagram

A wiring diagram is a very simple way to show wiring connections in an easy-to-follow manner. These types of diagrams are normally found with home appliances and automobile electrical systems (Figure 12). Wiring diagrams show the component parts in pictorial form, and the components are identified by name. Most wiring diagrams also show the relative location of component parts and color coding of conductors or leads.

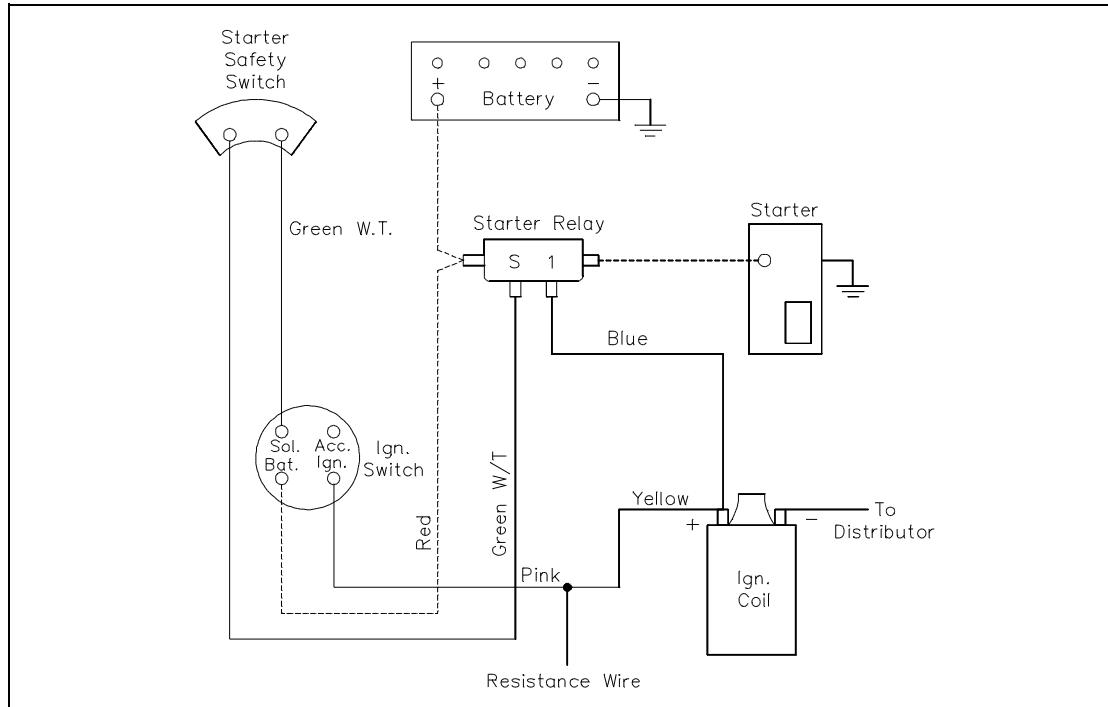


Figure 12 Wiring Diagram

Resistivity

Resistivity is defined as the measure of the resistance a material imposes on current flow. The resistance of a given length of conductor depends upon the resistivity of that material, the length of the conductor, and the cross-sectional area of the conductor, according to Equation (2-1).

$$R = \rho \frac{L}{A} \quad (2-1)$$

where

R = resistance of conductor, Ω

ρ = specific resistance or resistivity $\text{cm-}\Omega/\text{ft}$

L = length of conductor, ft

A = cross-sectional area of conductor, cm

The resistivity ρ (rho) allows different materials to be compared for resistance, according to their nature, without regard to length or area. The higher the value of ρ , the higher the resistance.

Table 1 gives resistivity values for metals having the standard wire size of one foot in length and a cross-sectional area of 1 cm.

TABLE 1
Properties of Conducting Materials

Material	ρ = Resistivity at 20°C-cm- Ω /ft (a)
Aluminum	17
Carbon	(b)
Constantan	295
Copper	10.4
Gold	14
Iron	58
Nichrome	676
Nickel	52
Silver	9.8
Tungsten	33.8

(a) Precise values depend on exact composition of material.
(b) Carbon has 2500-7500 times the resistance of copper.

Temperature Coefficient of Resistance

Temperature coefficient of resistance, α (alpha), is defined as the amount of change of the resistance of a material for a given change in temperature. A positive value of α indicates that R increases with temperature; a negative value of α indicates R decreases; and zero α indicates that R is constant. Typical values are listed in Table 2.

TABLE 2
Temperature Coefficients for Various Materials

<u>Material</u>	<u>Temperature Coefficient, Ω per $^{\circ}\text{C}$</u>
Aluminum	0.004
Carbon	-0.0003
Constantan	0 (avg)
Copper	0.004
Gold	0.004
Iron	0.006
Nichrome	0.0002
Nickel	0.005

For a given material, α may vary with temperature; therefore, charts are often used to describe how resistance of a material varies with temperature.

An increase in resistance can be approximated from equation (2-2).

$$R_t = R_o + R_o(\alpha\Delta T) \quad (2-2)$$

where

R_t = higher resistance at higher temperatures

R_o = resistance at 20°C

α = temperature coefficient

ΔT = temperature rise above 20°C

Electric Circuit

Each electrical circuit has at least four basic parts: (1) a source of electromotive force, (2) conductors, (3) load or loads, and (4) some means of control. In Figure 13, the source of EMF is the battery; the conductors are wires which connect the various component parts; the resistor is the load; and a switch is used as the circuit control device.

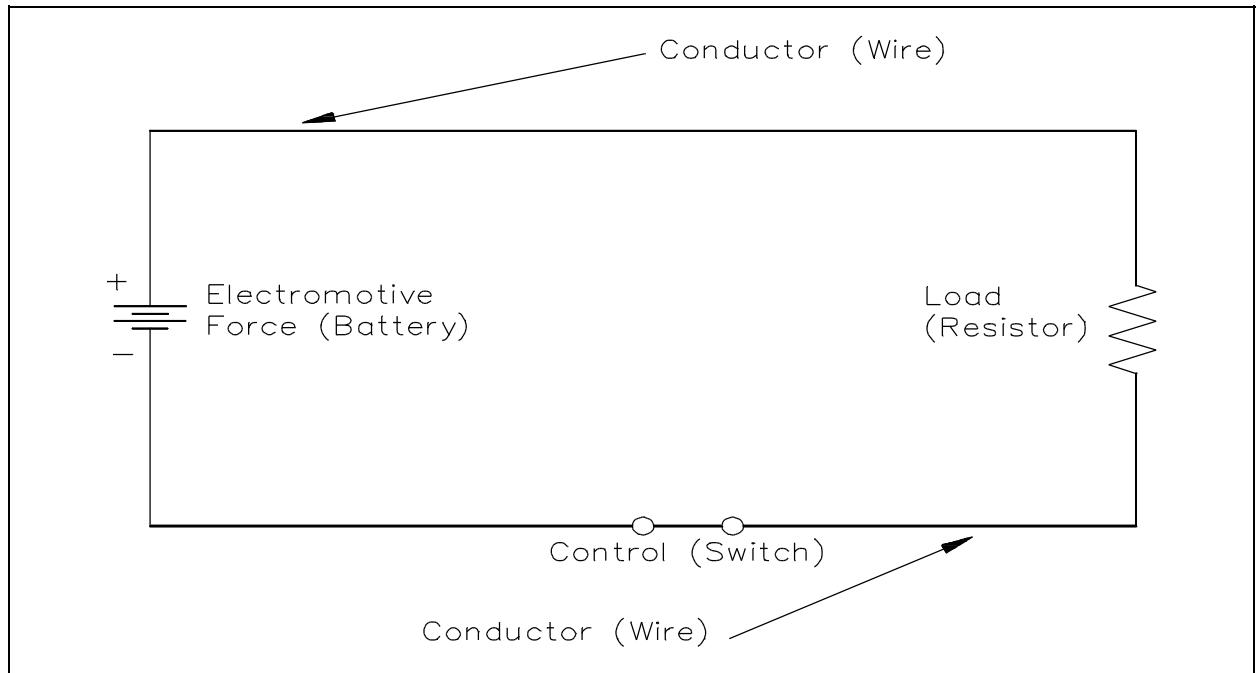


Figure 13 Closed Circuit

A *closed circuit* (Figure 13) is an uninterrupted, or unbroken, path for current from the source (EMF), through the load, and back to the source.

An *open circuit*, or incomplete circuit, (Figure 14) exists if a break in the circuit occurs; this prevents a complete path for current flow.

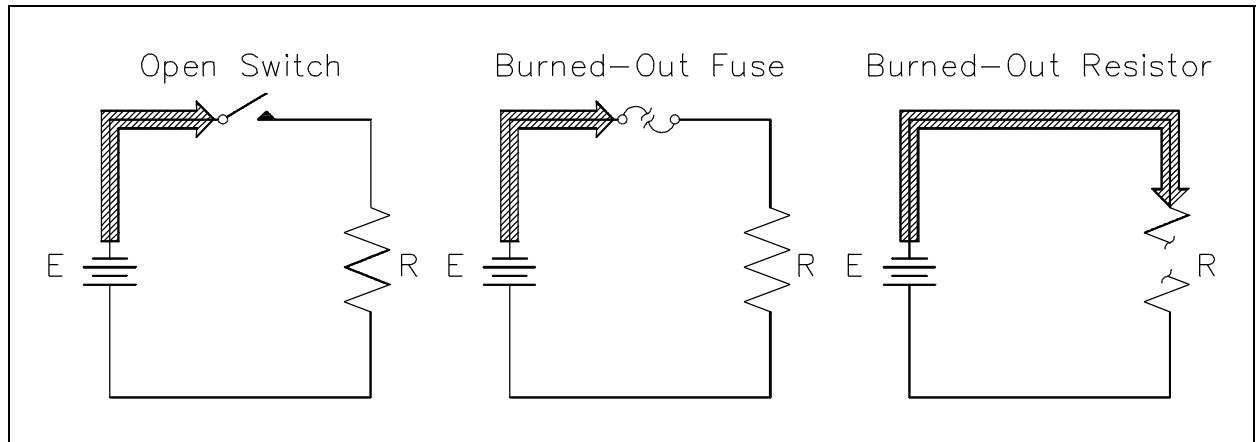


Figure 14 Open Circuit

A *short circuit* is a circuit which offers very little resistance to current flow and can cause dangerously high current flow through a circuit (Figure 15). Short circuits are usually caused by an inadvertent connection between two points in a circuit which offers little or no resistance to current flow. Shorting resistor R in Figure 15 will probably cause the fuse to blow.

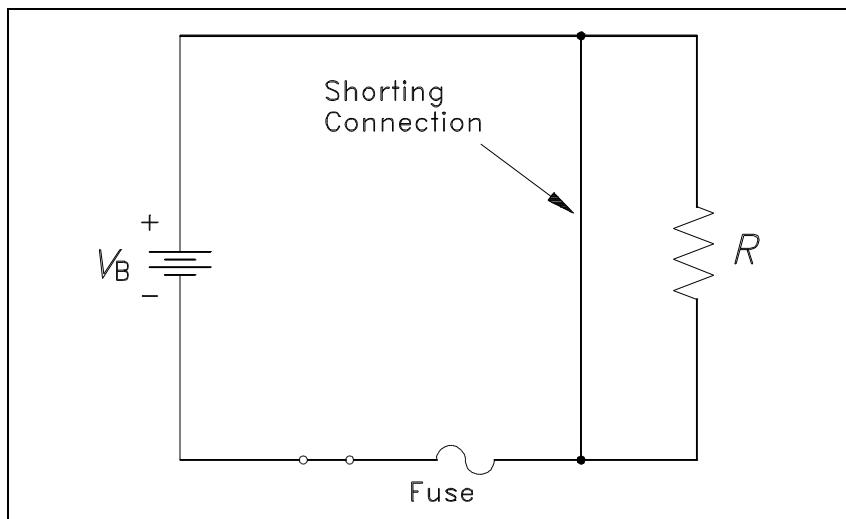


Figure 15 Short Circuit

Series Circuit

A *series circuit* is a circuit where there is only one path for current flow. In a series circuit (Figure 16), the current will be the same throughout the circuit. This means that the current flow through R_1 is the same as the current flow through R_2 and R_3 .

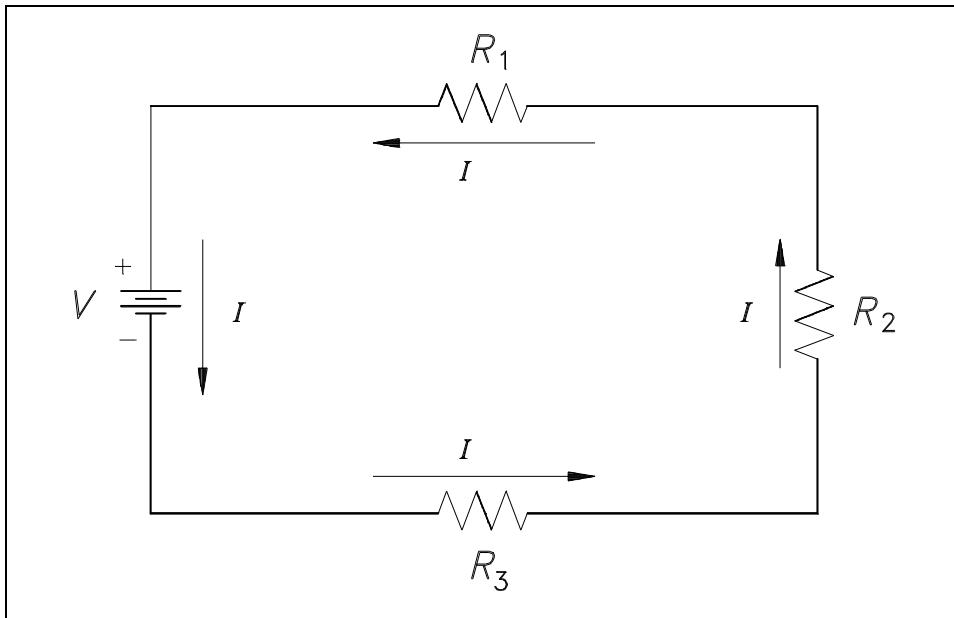


Figure 16 Series Circuit

Parallel Circuit

Parallel circuits are those circuits which have two or more components connected across the same voltage source (Figure 17). Resistors R_1 , R_2 , and R_3 are in parallel with each other and the source. Each parallel path is a branch with its own individual current. When the current leaves the source V , part I_1 of I_T will flow through R_1 ; part I_2 will flow through R_2 ; and part I_3 will flow through R_3 . Current through each branch can be different; however, voltage throughout the circuit will be equal.

$$V = V_1 = V_2 = V_3.$$

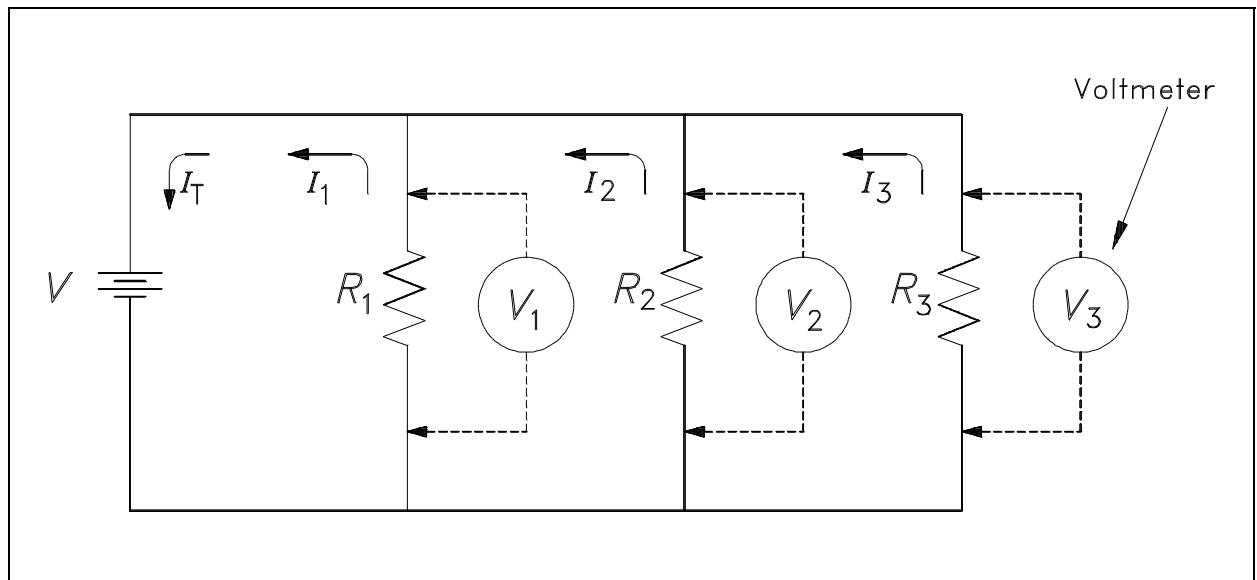


Figure 17 Parallel Circuit

Equivalent Resistance

In a parallel circuit, the total resistance of the resistors in parallel is referred to as *equivalent resistance*. This can be described as the total circuit resistance as seen by the voltage source. In all cases, the equivalent resistance will be less than any of the individual parallel circuit resistors. Using Ohm's Law, equivalent resistance (R_{EQ}) can be found by dividing the source voltage (V) by the total circuit current (I_T), as shown in Figure 17.

$$R_{EQ} = \frac{V}{I_t}$$

Summary

The important information concerning basic DC circuits is summarized below.

DC Circuit Terminology Summary

- There are four types of circuit diagrams.
 - Schematic diagram
 - One-line diagram
 - Block diagram
 - Wiring diagram
- Resistivity is defined as the measure of the resistance a material imposes on current flow.
- Temperature coefficient of resistance, α (alpha), is defined as the amount of change of the resistance of a material for a given change in temperature.
- A closed circuit is one that has a complete path for current flow.
- An open circuit is one that does not have a complete path for current flow.
- A short circuit is a circuit with a path that has little or no resistance to current flow.
- A series circuit is one where there is only one path for current flow.
- A parallel circuit is one which has two or more components connected across the same voltage source.
- Equivalent resistance is the total resistance of the resistors in parallel.

BASIC DC CIRCUIT CALCULATIONS

Each type of DC circuit contains certain characteristics that determine the way its voltage and current behave. To begin analysis of the voltages and currents at each part of a circuit, an understanding of these characteristics is necessary.

EO 1.7 **Given a circuit, CALCULATE total resistance for a series or parallel circuit.**

EO 1.8 **DESCRIBE what is meant by the term "voltage divider."**

EO 1.9 **DESCRIBE what is meant by the term "current division."**

Series Resistance

The total resistance in a series circuit is equal to the sum of all the parts of that circuit, as shown in equation (2-3).

$$R_T = R_1 + R_2 + R_3 \dots \text{etc.} \quad (2-3)$$

where

$$R_T = \text{resistance total}$$

$$R_1, R_2, \text{ and } R_3 = \text{resistance in series}$$

Example: A series circuit has a 60Ω , a 100Ω , and a 150Ω resistor in series (Figure 18). What is the total resistance of the circuit?

Solution:

$$\begin{aligned} R_T &= R_1 + R_2 + R_3 \\ &= 60 + 100 + 150 \\ &= 310 \Omega \end{aligned}$$

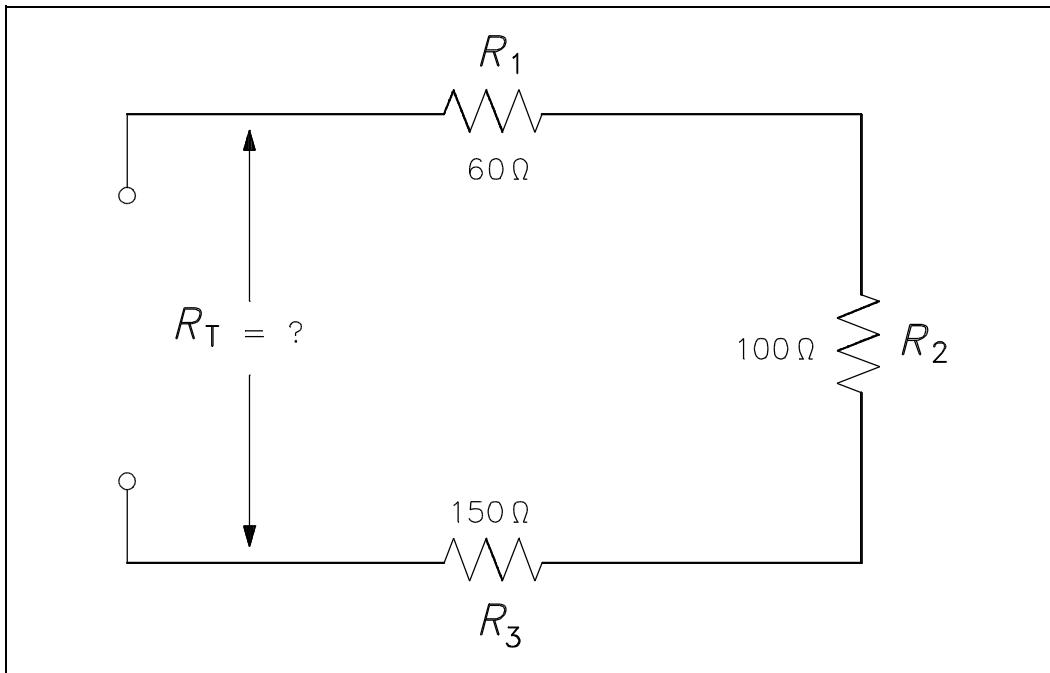


Figure 18 Resistance in a Series Circuit

The total voltage across a series circuit is equal to the sum of the voltages across each resistor in the circuit (Figure 19) as shown in equation (2-4).

$$V_T = V_1 + V_2 + V_3 \dots \text{etc.} \quad (2-4)$$

where

V_T = total voltage

V_1 = voltage across R_1

V_2 = voltage across R_2

V_3 = voltage across R_3

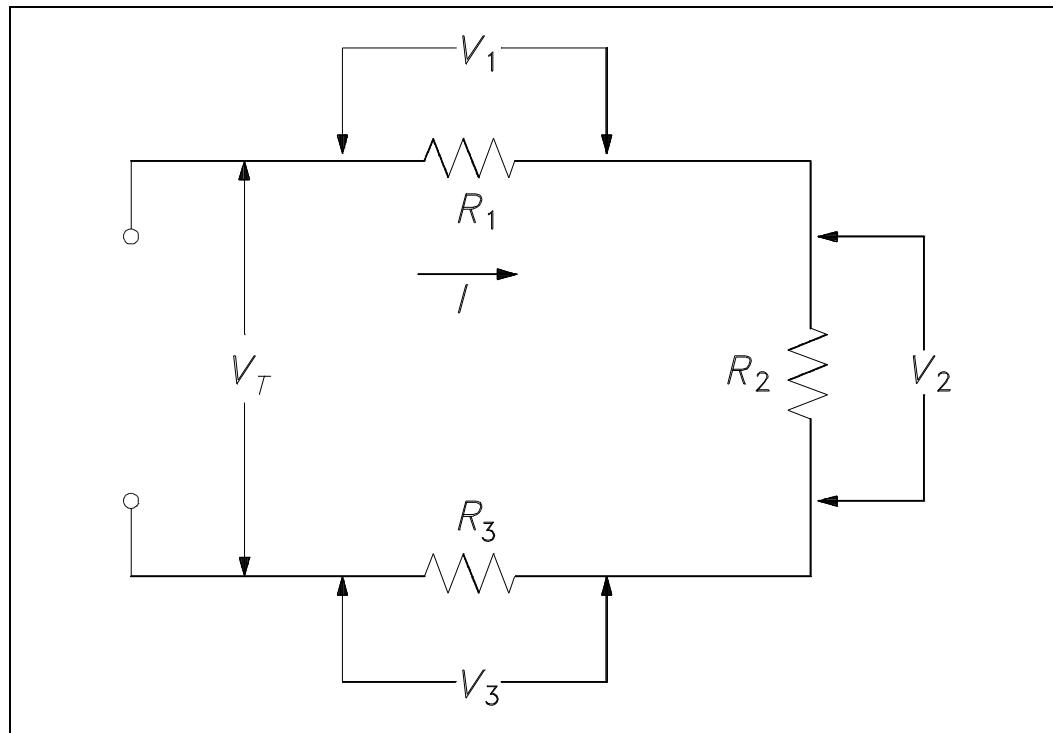


Figure 19 Voltage Drops in a Series Circuit

Ohm's law may now be applied to the entire series circuit or to individual component parts of the circuit. When used on individual component parts, the voltage across that part is equal to the current times the resistance of that part. For the circuit shown in Figure 20, the voltage can be determined as shown below.

$$V_1 = IR_1$$

$$V_2 = IR_2$$

$$V_3 = IR_3$$

$$V_T = V_1 + V_2 + V_3$$

$$V_T = 10 \text{ volts} + 24 \text{ volts} + 36 \text{ volts}$$

$$V_T = 70 \text{ volts}$$

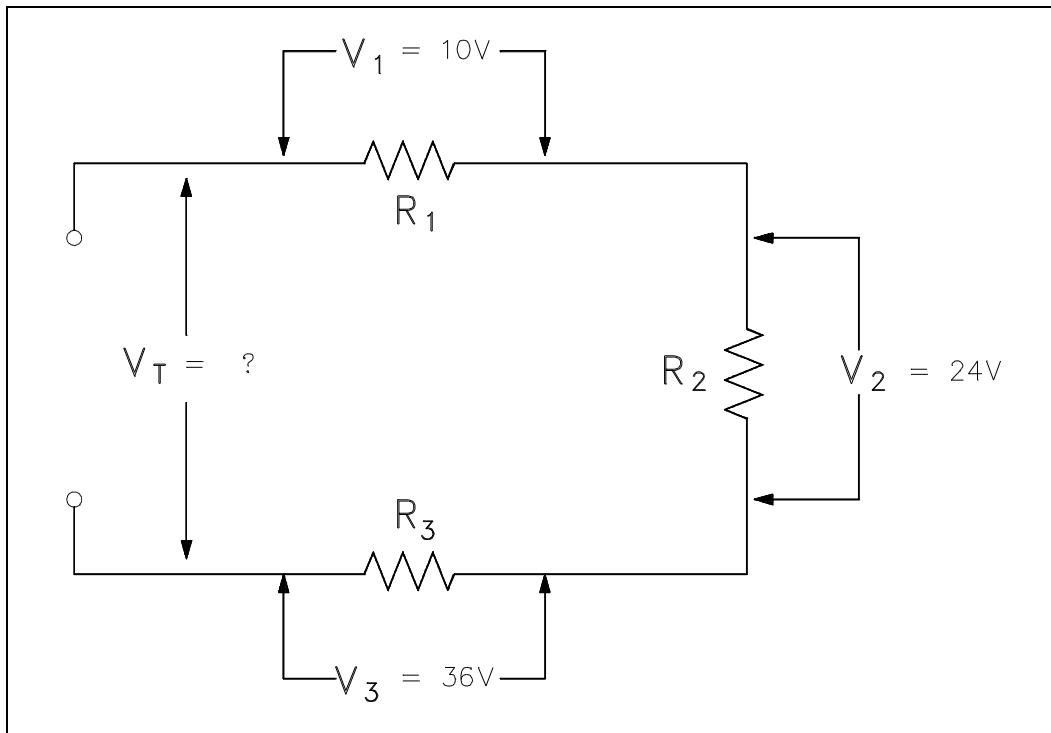


Figure 20 Voltage Total in a Series Circuit

To find the total voltage across a series circuit, multiply the current by the total resistance as shown in equation (2-5).

$$V_T = IR_T \quad (2-5)$$

where

V_T = total voltage

I = current

R_T = total resistance

Example 1: A series circuit has a 50Ω , a 75Ω , and a 100Ω resistor in series (Figure 21). Find the voltage necessary to produce a current of 0.5 amps.

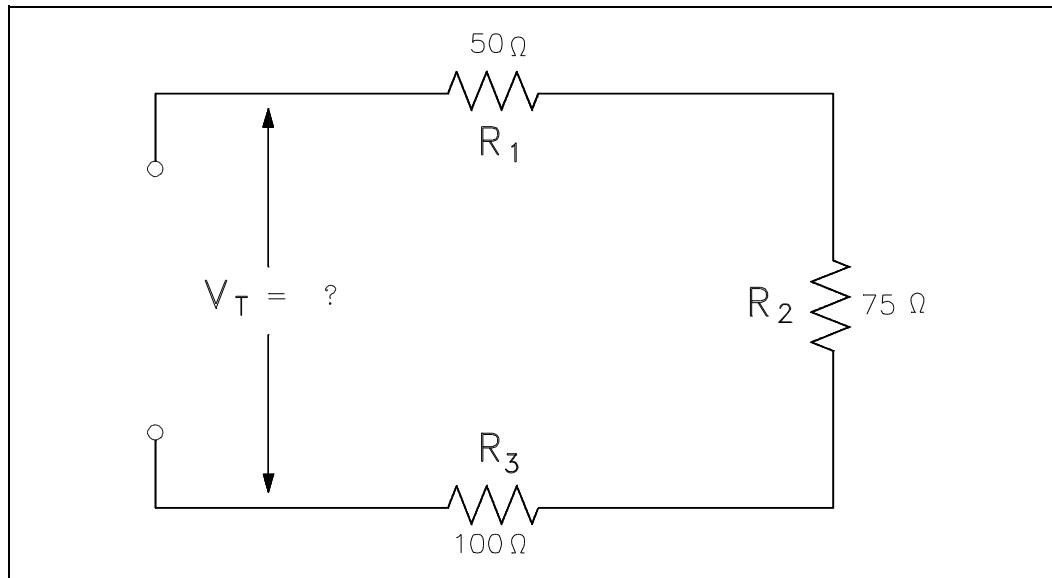


Figure 21 Example 1 Series Circuit

Solution:

Step 1: Find circuit current. As we already know, current is the same throughout a series circuit, which is already given as 0.5 amps.

Step 2: Find R_T .

$$R_T = R_1 + R_2 + R_3$$

$$R_T = 50\ \Omega + 75\ \Omega + 100\ \Omega$$

$$R_T = 225\ \Omega$$

Step 3: Find V_T . Use Ohm's law.

$$V_T = IR_T$$

$$V_T = (0.5\ \text{amps})(225\ \Omega)$$

$$V_T = 112.5\ \text{volts}$$

Example 2: A 120 V battery is connected in series with three resistors: 40Ω , 60Ω , and 100Ω (Figure 22). Find the voltage across each resistor.

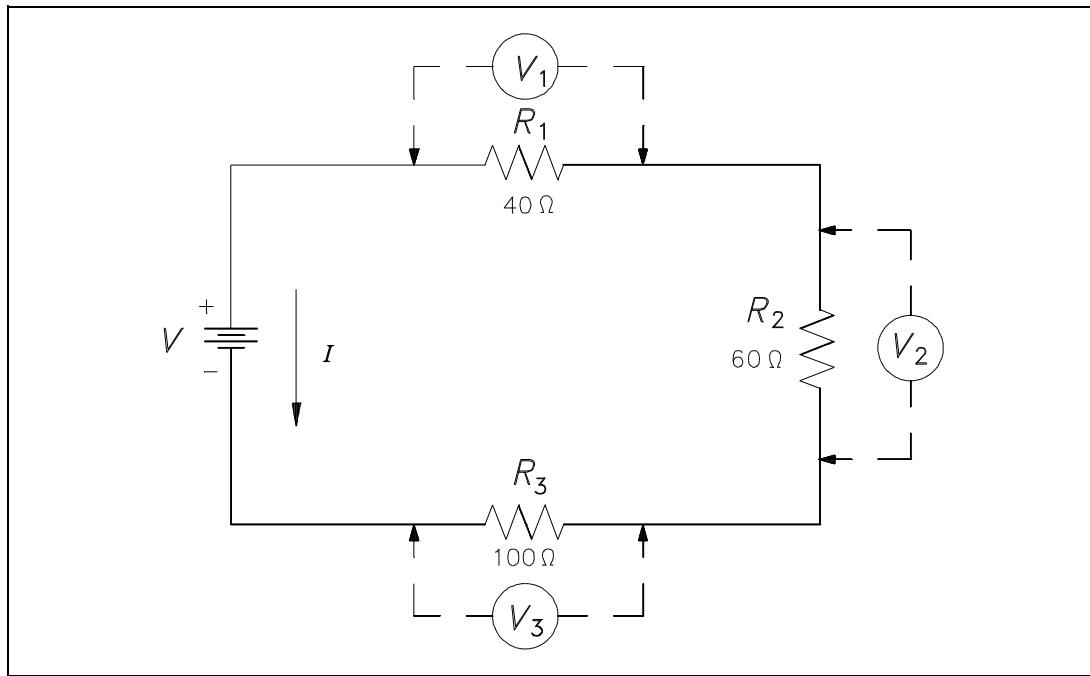


Figure 22 Example 2 Series Circuit

Solution:

Step 1: Find total resistance.

$$R_T = R_1 + R_2 + R_3$$

$$R_T = 40\ \Omega + 60\ \Omega + 100\ \Omega$$

$$R_T = 200\ \text{ohms}$$

Step 2: Find circuit current (I).

$$V_T = IR_T$$

Solving for I :

$$I = \frac{V_T}{R_T}$$

$$I = \frac{120\ \text{volts}}{200\ \Omega}$$

$$I = 0.6\ \text{amps}$$

Step 3: Find the voltage across each component.

$$\begin{aligned}V_1 &= IR_1 \\V_1 &= (0.6 \text{ amps})(40 \Omega) \\V_1 &= 24 \text{ volts}\end{aligned}$$

$$\begin{aligned}V_2 &= IR_2 \\V_2 &= (0.6 \text{ amps})(60 \Omega) \\V_2 &= 36 \text{ volts}\end{aligned}$$

$$\begin{aligned}V_3 &= IR_3 \\V_3 &= (0.6 \text{ amps})(100 \Omega) \\V_3 &= 60 \text{ volts}\end{aligned}$$

The voltages of V_1 , V_2 , and V_3 in Example 2 are known as "voltage drops" or "IR drops." Their effect is to reduce the available voltage to be applied across the other circuit components. The sum of the voltage drops in any series circuit is always equal to the applied voltage. We can verify our answer in Example 2 by using equation (2-4).

$$\begin{aligned}V_T &= V_1 + V_2 + V_3 \\120 \text{ volts} &= 24 \text{ volts} + 36 \text{ volts} + 60 \text{ volts} \\120 \text{ volts} &= 120 \text{ volts}\end{aligned}$$

Parallel Currents

The sum of the currents flowing through each branch of a parallel circuit is equal to the total current flow in the circuit. Using Ohm's Law, the branch current for a three branch circuit equals the applied voltage divided by the resistance as shown in equations (2-6), (2-7), and (2-8).

$$\text{Branch 1: } I_1 = \frac{V_1}{R_1} = \frac{V}{R_1} \quad (2-6)$$

$$\text{Branch 2: } I_2 = \frac{V_2}{R_2} = \frac{V}{R_2} \quad (2-7)$$

$$\text{Branch 3: } I_3 = \frac{V_3}{R_3} = \frac{V}{R_3} \quad (2-8)$$

Example 1: Two resistors, each drawing 3A, and a third resistor, drawing 2A, are connected in parallel across a 115 volt source (Figure 23). What is total current?

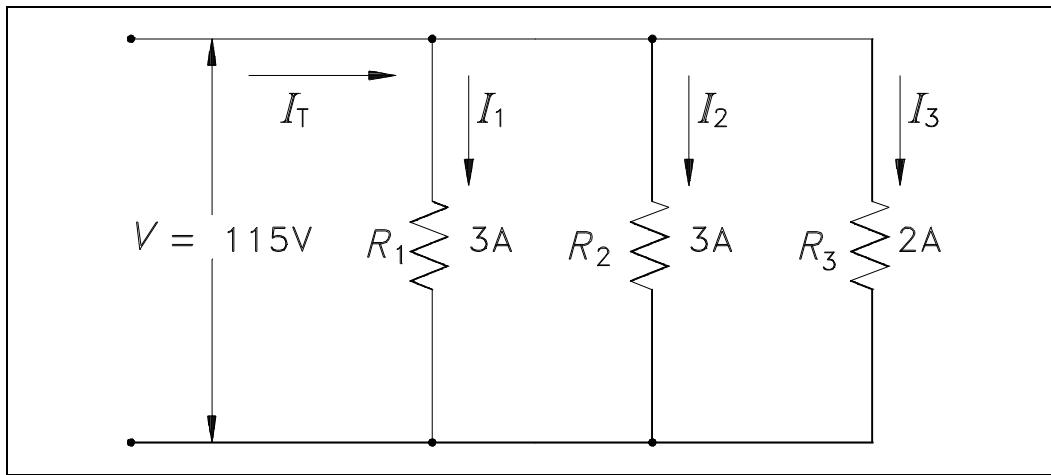


Figure 23 Example 1 Parallel Circuit

$$I_T = I_1 + I_2 + I_3$$

$$I_T = 3A + 3A + 2A$$

$$I_T = 8A$$

Example 2: Two branches, R_1 and R_2 , are across a 120 V power source. The total current flow is 30 A (Figure 24). Branch R_1 takes 22 amps. What is the current flow in Branch R_2 ?

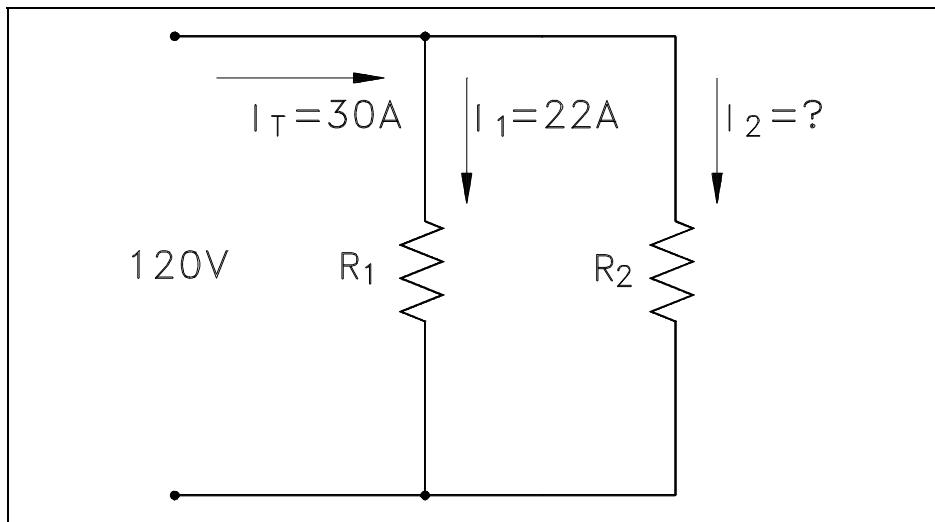


Figure 24 Example 2 Parallel Circuit

$$\begin{aligned}
 I_T &= I_1 + I_2 \\
 I_2 &= I_T - I_1 \\
 I_2 &= 30 - 22 \\
 I_2 &= 8 \text{ amps}
 \end{aligned}$$

Example 3: A parallel circuit consists of $R_1 = 15\Omega$, $R_2 = 20\Omega$ and $R_3 = 10\Omega$, with an applied voltage of 120 V (Figure 25). What current will flow through each branch?

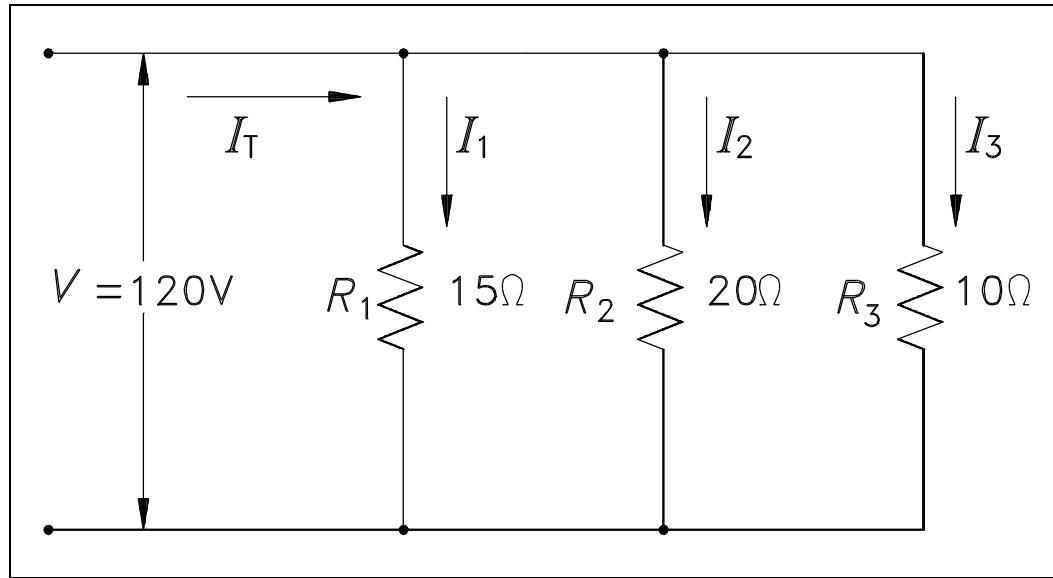


Figure 25 Example 3 Parallel Circuit

$$I_1 = \frac{V}{R_1} = \frac{120}{15} = 8A$$

$$I_2 = \frac{V}{R_2} = \frac{120}{20} = 6A$$

$$I_3 = \frac{V}{R_3} = \frac{120}{10} = 12A$$

$$I_T = I_1 + I_2 + I_3$$

$$I_T = 8A + 6A + 12A$$

$$I_T = 26A$$

Resistance in Parallel

Total resistance in a parallel circuit can be found by applying Ohm's Law. Divide the voltage across the parallel resistance by the total line current as shown in equation (2-9).

$$R_T = \frac{V}{I_T} \quad (2-9)$$

Example: Find the total resistance of the circuit shown in Figure 25 if the line voltage is 120 V and total current is 26A.

$$R_T = \frac{V}{I_T} = \frac{120}{26} = 4.62 \Omega$$

The total load connected to a 120 V source is the same as the single "equivalent resistance" of 4.62Ω connected across the source (Figure 26). Equivalent resistance is the total resistance a combination of loads present to a circuit.

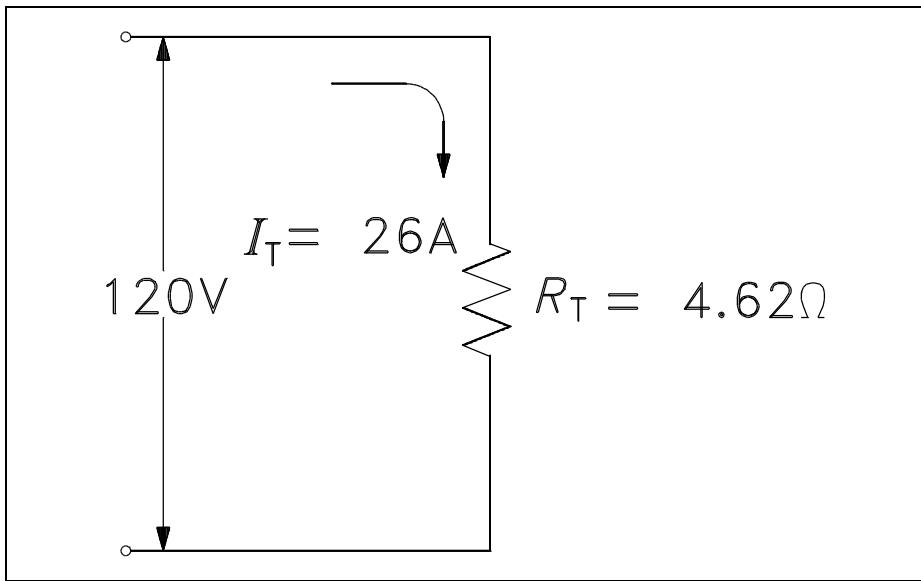


Figure 26 Equivalent Resistance in a Parallel Circuit

The total resistance in a parallel circuit can also be found by using the equation (2-10).

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots + \frac{1}{R_N} \quad (2-10)$$

Example 1: Find the total resistance of a 4Ω , an 8Ω , and a 16Ω resistor in parallel (Figure 27).

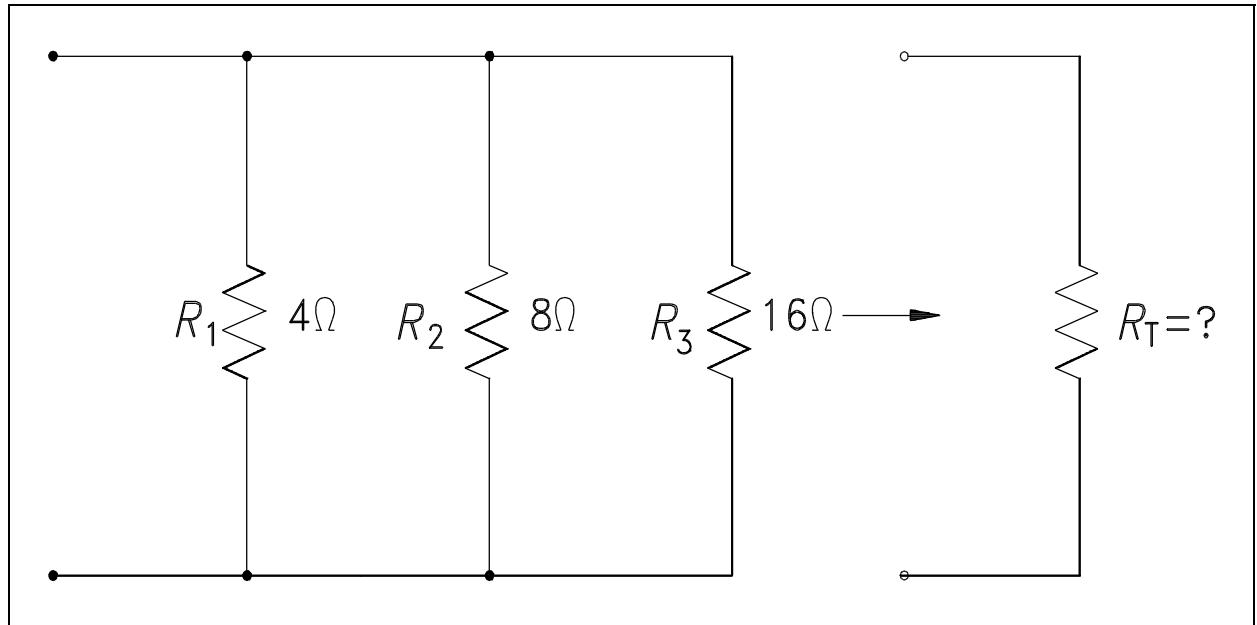


Figure 27 Total Resistance in a Parallel Circuit

Solution:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_T} = \frac{1}{4} + \frac{1}{8} + \frac{1}{16}$$

$$\frac{1}{R_T} = \frac{4}{16} + \frac{2}{16} + \frac{1}{16} = \frac{7}{16}$$

$$R_T = \frac{16}{7} = 2.29\Omega$$

Note: Whenever resistors are in parallel, the total resistance is always smaller than any single branch.

Example 2: Now add a fourth resistance of 4Ω in parallel to the circuit in Figure 27. What is the new total resistance of the circuit?

Solution:

$$\begin{aligned}\frac{1}{R_T} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \\ \frac{1}{R_T} &= \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \frac{1}{4} \\ \frac{1}{R_T} &= \frac{4}{16} + \frac{2}{16} + \frac{1}{16} + \frac{4}{16} = \frac{11}{16} \\ R_T &= \frac{16}{11} = 1.45\Omega\end{aligned}$$

Simplified Formulas

Total resistance of equal resistors in a parallel circuit is equal to the resistance of one resistor divided by the number of resistors.

$$R_T = \frac{R}{N}$$

where

R_T = total resistance

R = resistance of one resistor

N = number of resistors

Example: Five lamps, each with a resistance of 40Ω , are connected in parallel. Find total resistance.

$$R = R_1 = R_2 = R_3 = R_4 = R_5 = 40\Omega$$

$$N = 5$$

$$R_T = \frac{R}{N} = \frac{40}{5} = 8\Omega$$

When any two resistors are unequal in a parallel circuit, it is easier to calculate R_T by multiplying the two resistances and then dividing the product by the sum, as shown in equation (2-11). As shown in equation (2-11), this is valid when there are only two resistors in parallel.

$$R_T = \frac{R_1 R_2}{R_1 + R_2} \quad (2-11)$$

Example: Find the total resistance of a parallel circuit which has one 12Ω and one 4Ω resistor.

$$R_T = \frac{R_1 R_2}{R_1 + R_2} = \frac{(12)(4)}{12 + 4} = \frac{48}{16} = 3\Omega$$

In certain cases involving two resistors in parallel, it is useful to find an unknown resistor, R_x , to obtain a certain R_T . To find the appropriate formula, we start with equation (2-10) and let the known resistor be R and the unknown resistor be R_x .

$$R_T = \frac{R R_x}{R + R_x}$$

Cross multiply: $R_T R + R_T R_x = R R_x$

Transpose: $R R_x - R_T R_x = R_T R$

Factor: $R_x (R - R_T) = R_T R$

Solve for R_x : $R_x = \frac{R_T R}{R - R_T}$

Example: What value of resistance must be added, in parallel, with an 8Ω resistor to provide a total resistance of 6Ω (Figure 28)?

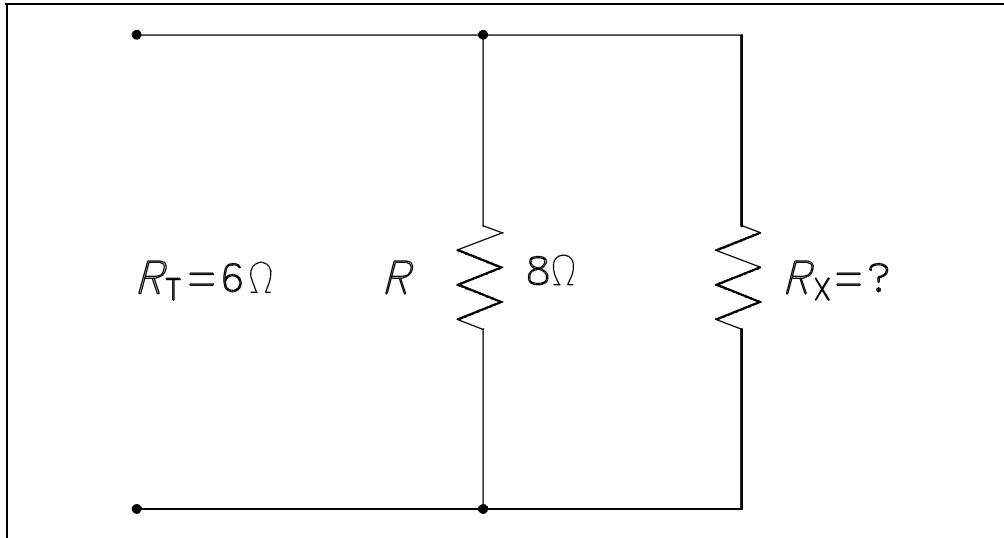


Figure 28 Example Parallel Circuit

Solution:

$$R_X = \frac{R R_T}{R - R_T} = \frac{(8)(6)}{8-6} = \frac{48}{2} = 24\Omega$$

Voltage Divider

A *voltage divider*, or network, is used when it is necessary to obtain different values of voltage from a single energy source. A simple voltage divider is shown in Figure 29. In this circuit, 24 volts is applied to three resistors in series. The total resistance limits the current through the circuit to one ampere. Individual voltages are found as follows using equation (2-12).

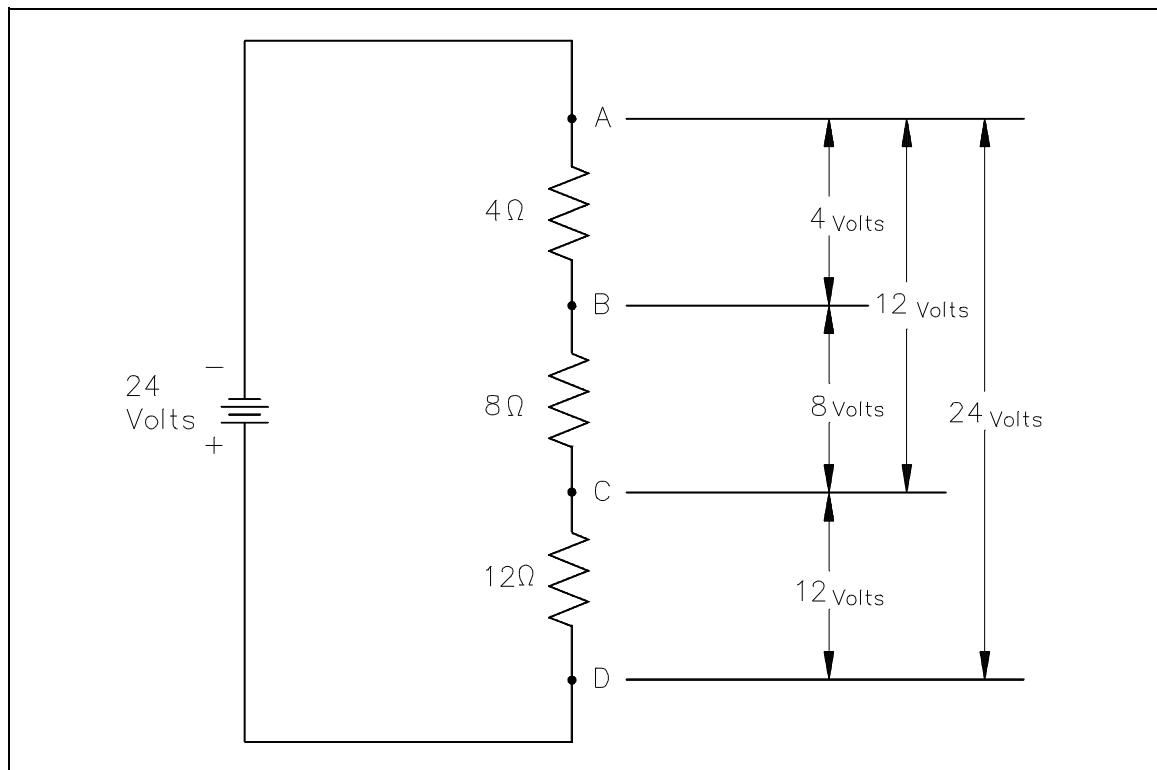


Figure 29 Voltage Divider

$$\text{Total current: } I = \frac{V}{R} = \frac{24}{4 + 8 + 12} = \frac{24}{24} = 1 \text{ amp} \quad (2-12)$$

$$\text{Voltage drop across AB: } V = IR = (1)(4) = 4 \text{ Volts}$$

$$\text{Voltage drop across BC: } V = IR = (1)(8) = 8 \text{ Volts}$$

$$\begin{aligned} \text{Voltage drop across CD:} & \quad V = IR \\ & \quad = (1)(12) \\ & \quad V = 12 \text{ Volts} \end{aligned}$$

$$\begin{array}{l} V = IR \\ \text{Total voltage drop AC:} \quad \quad \quad = (1)(8 + 4) = (1)(12) \\ \quad \quad \quad V = 12 \text{ Volts} \end{array}$$

Current Division

Sometimes it is necessary to find the individual branch currents in a parallel circuit when only resistance and total current are known. When only two branches are involved, the current in one branch will be some fraction of I_T . The resistance in each circuit can be used to divide the total current into fractional currents in each branch. This process is known as *current division*.

$$I_1 = \frac{R_2}{R_1 + R_2} I_T \quad (2-13)$$

$$I_2 = \frac{R_1}{R_1 + R_2} I_T$$

Note that the equation for each branch current has the opposite R in the numerator. This is because each branch current is inversely proportional to the branch resistance.

Example: Find branch current for I_1 and I_2 for the circuit shown in Figure 30.

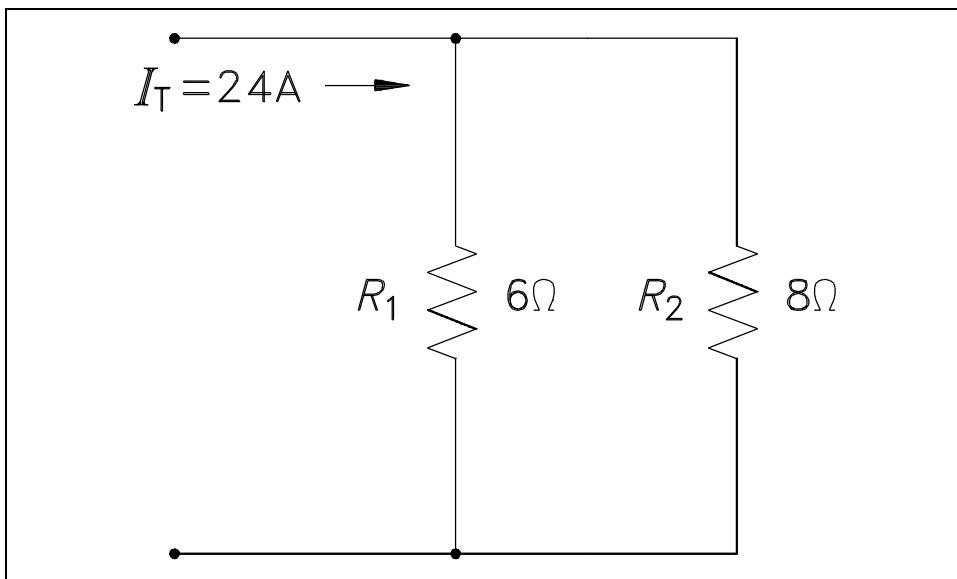


Figure 30 Current Division Example Circuit

Solution:

$$I_1 = \frac{R_2}{R_1 + R_2} I_T = \frac{8}{6 + 8} (24) = \frac{8}{14} (24) = 13.71 \text{ amps}$$

$$I_2 = \frac{R_1}{R_1 + R_2} I_T = \frac{6}{6 + 8} (24) = \frac{6}{14} (24) = 10.29 \text{ amps}$$

Since I_1 and I_T were known, we could have also simply subtracted I_1 from I_T to find I_2 :

$$\begin{aligned} I_T &= I_1 + I_2 \\ I_2 &= I_T - I_1 \\ &= 24 - 13.71 \\ &= 10.29 \text{ amps} \end{aligned}$$

Summary

The important information in this chapter is summarized below.

Basic DC Circuit Calculations Summary

- Equivalent resistance is a term used to represent the total resistance a combination of loads presents to a circuit.
- A voltage divider is used to obtain different values of voltage from a single energy source.
- Current division is used to determine the current flowing through each leg of a parallel circuit.

VOLTAGE POLARITY AND CURRENT DIRECTION

Before introducing the laws associated with complex DC circuit analysis, the importance of voltage polarity and current direction must be understood. This chapter will introduce the polarities and current direction associated with DC circuits.

EO 1.10 **DESCRIBE** the difference between electron flow and conventional current flow.

EO 1.11 Given a circuit showing current flows, **IDENTIFY** the polarity of the voltage drops in the circuit.

Conventional and Electron Flow

The direction of electron flow is from a point of negative potential to a point of positive potential. The direction of positive charges, or holes, is in the opposite direction of electron flow. This flow of positive charges is known as *conventional flow*. All of the electrical effects of electron flow from negative to positive, or from a high potential to a lower potential, are the same as those that would be created by flow of positive charges in the opposite direction; therefore, it is important to realize that both conventions are in use, and they are essentially equivalent. In this manual, the electron flow convention is used.

Polarities

All voltages and currents have polarity as well as magnitude. In a series circuit, there is only one current, and its polarity is from the negative battery terminal through the rest of the circuit to the positive battery terminal. Voltage drops across loads also have polarities. The easiest way to find these polarities is to use the direction of the electron current as a basis. Then, where the electron current enters the load, the voltage is negative (Figure 31). This holds true regardless of the number or type of loads in the circuit. The drop across the load is opposite to that of the source. The voltage drops oppose the source voltage and reduce it for the other loads. This is because each load uses energy, leaving less energy for other loads.

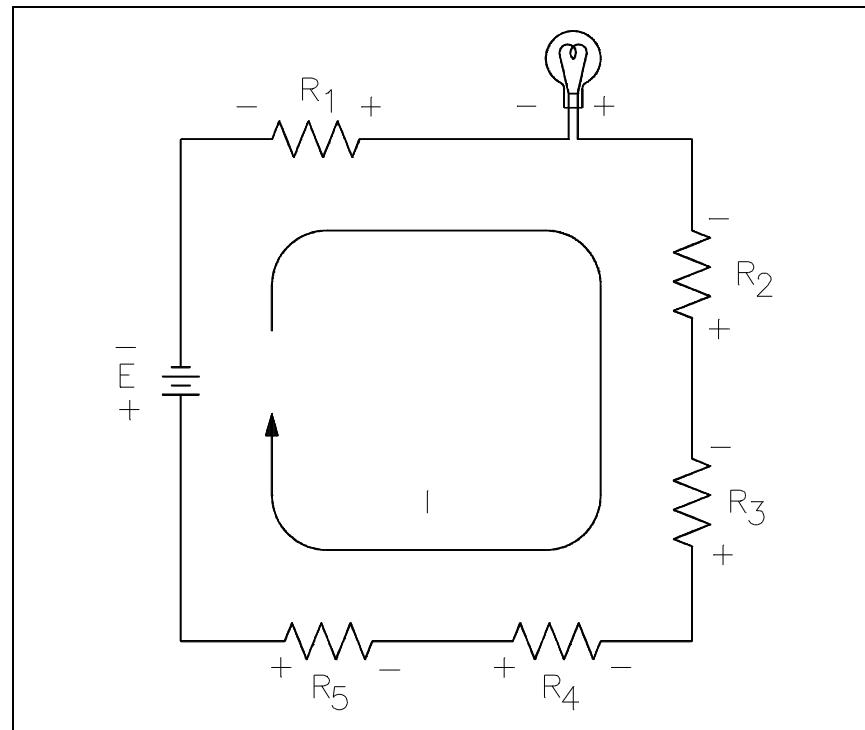


Figure 31 Voltage Polarities

Summary

The important information in this chapter is summarized below.

Voltage Polarity and Current Direction Summary

- The direction of electron flow is from a point of negative potential to a point of positive potential.
- The direction of positive charges, or holes, is in the opposite direction of electron flow. This flow of positive charges is known as "conventional flow."
- Where the electron current enters the load, the voltage is negative.

KIRCHHOFF'S LAWS

Kirchhoff's two laws reveal a unique relationship between current, voltage, and resistance in electrical circuits that is vital to performing and understanding electrical circuit analysis.

EO 1.12 STATE Kirchhoff's voltage law.

EO 1.13 STATE Kirchhoff's current law.

EO 1.14 Given a circuit, SOLVE problems for voltage and current using Kirchhoff's laws.

Kirchhoff's Laws

In all of the circuits examined so far, Ohm's Law described the relationship between current, voltage, and resistance. These circuits have been relatively simple in nature. Many circuits are extremely complex and cannot be solved with Ohm's Law. These circuits have many power sources and branches which would make the use of Ohm's Law impractical or impossible.

Through experimentation in 1857 the German physicist Gustav Kirchhoff developed methods to solve complex circuits. Kirchhoff developed two conclusions, known today as Kirchhoff's Laws.

Law 1: The sum of the voltage drops around a closed loop is equal to the sum of the voltage sources of that loop (Kirchhoff's Voltage Law).

Law 2: The current arriving at any junction point in a circuit is equal to the current leaving that junction (Kirchhoff's Current Law).

Kirchhoff's two laws may seem obvious based on what we already know about circuit theory. Even though they may seem very simple, they are powerful tools in solving complex and difficult circuits.

Kirchhoff's laws can be related to conservation of energy and charge if we look at a circuit with one load and source. Since all of the power provided from the source is consumed by the load, energy and charge are conserved. Since voltage and current can be related to energy and charge, then Kirchhoff's laws are only restating the laws governing energy and charge conservation.

The mathematics involved becomes more difficult as the circuits become more complex. Therefore, the discussion here will be limited to solving only relatively simple circuits.

Kirchhoff's Voltage Law

Kirchhoff's first law is also known as his "voltage law." The voltage law gives the relationship between the "voltage drops" around any closed loop in a circuit, and the voltage sources in that loop. The total of these two quantities is always equal. In equation form:

$$E_{\text{source}} = E_1 + E_2 + E_3 + \text{etc.} = I_1R_1 + I_2R_2 + I_3R_3 + \text{etc.}$$

$$\Sigma E_{\text{source}} = \Sigma I R \quad (2-14)$$

where the symbol Σ (the Greek letter sigma) means "the sum of."

Kirchhoff's voltage law can be applied only to closed loops (Figure 32). A closed loop must meet two conditions:

1. It must have one or more voltage sources.
2. It must have a complete path for current flow from any point, around the loop, and back to that point.

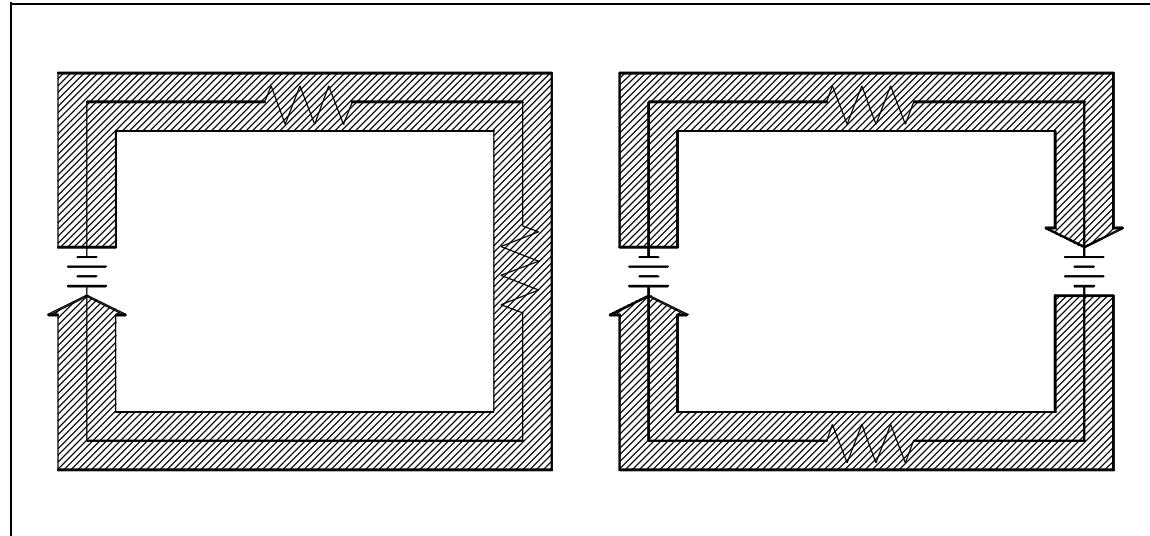


Figure 32 Closed Loop

You will remember that in a simple series circuit, the sum of the voltage drops around the circuit is equal to the applied voltage. Actually, this is Kirchhoff's voltage law applied to the simplest case, that is, where there is only one loop and one voltage source.

Applying Kirchhoff's Voltage Law

For a simple series circuit, Kirchhoff's voltage law corresponds to Ohm's Law. To find the current in a circuit (Figure 33) by using Kirchhoff's voltage law, use equation (2-15).

$$\Sigma E_{\text{source}} = \Sigma IR \quad (2-15)$$

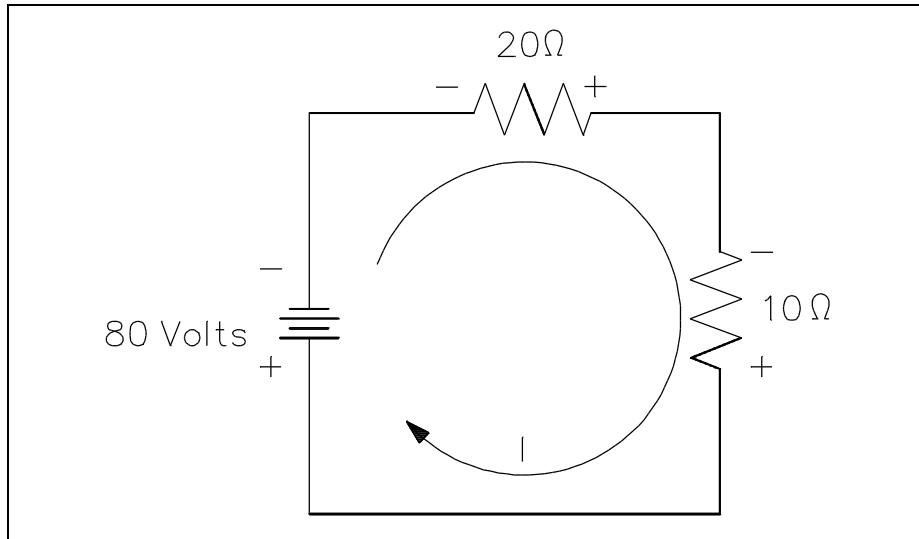


Figure 33 Using Kirchhoff's Voltage Law to find Current with one Source

$$80 = 20(I) + 10(I)$$

$$80 = 30(I)$$

$$I = 80/30 = 2.66 \text{ amperes}$$

In the problem above, the direction of current flow was known before solving the problem. When there is more than one voltage source, the direction of current flow may or may not be known. In such a case, a direction of current flow must be assumed in the beginning of the problem. All the sources that would aid the current in the assumed direction of current flow are then positive, and all that would oppose current flow are negative. If the assumed direction is correct, the answer will be positive. The answer would be negative if the direction assumed was wrong. In any case, the correct magnitude will be attained.

For example, what is the current flow in Figure 34? Assume that the current is flowing in the direction shown.

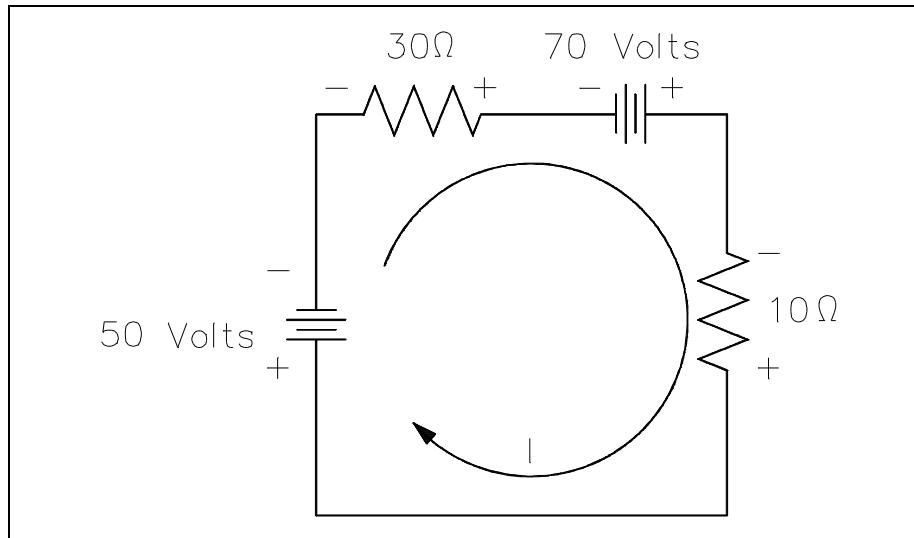


Figure 34 Using Kirchhoff's Voltage Law to find Current with Multiple Battery Sources

Using Kirchhoff's Voltage Law:

$$\sum E_{\text{source}} = \sum IR$$

$$50 - 70 = 30I + 10I$$

$$-20 = 40I$$

$$I = \frac{-20}{40}$$

$$I = -0.5$$

The result is negative. The current is actually 0.5 ampere in the opposite direction to that of the assumed direction.

Kirchhoff's Current Law

Kirchhoff's second law is called his current law and states: "At any junction point in a circuit, the current arriving is equal to the current leaving." Thus, if 15 amperes of current arrives at a junction that has two paths leading away from it, 15 amperes will divide among the two branches, but a total of 15 amperes must leave the junction. We are already familiar with Kirchhoff's current law from parallel circuits, that is, the sum of the branch currents is equal to the total current entering the branches, as well as the total current leaving the branches (Figure 35).

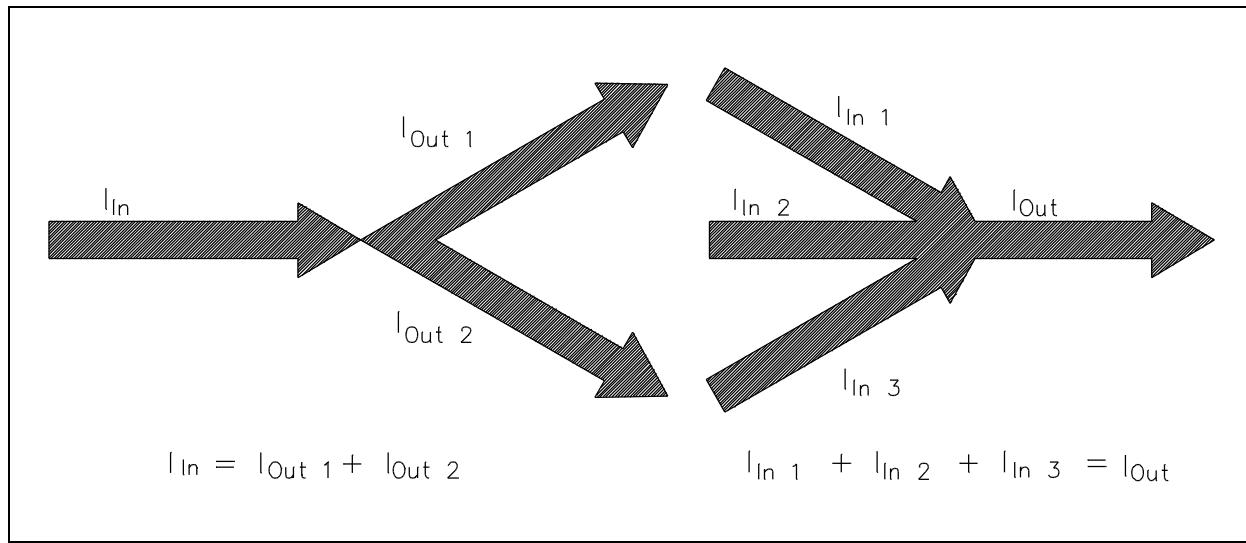


Figure 35 Illustration of Kirchhoff's Current Law

In equation form, Kirchhoff's current law may be expressed:

$$I_{IN} - I_{OUT} = 0 \quad (2-16)$$

or

$$I_{IN} = I_{OUT}$$

Normally Kirchhoff's current law is not used by itself, but with the voltage law, in solving a problem.

Example: Find I_2 in the circuit shown in Figure 36 using Kirchhoff's voltage and current laws.

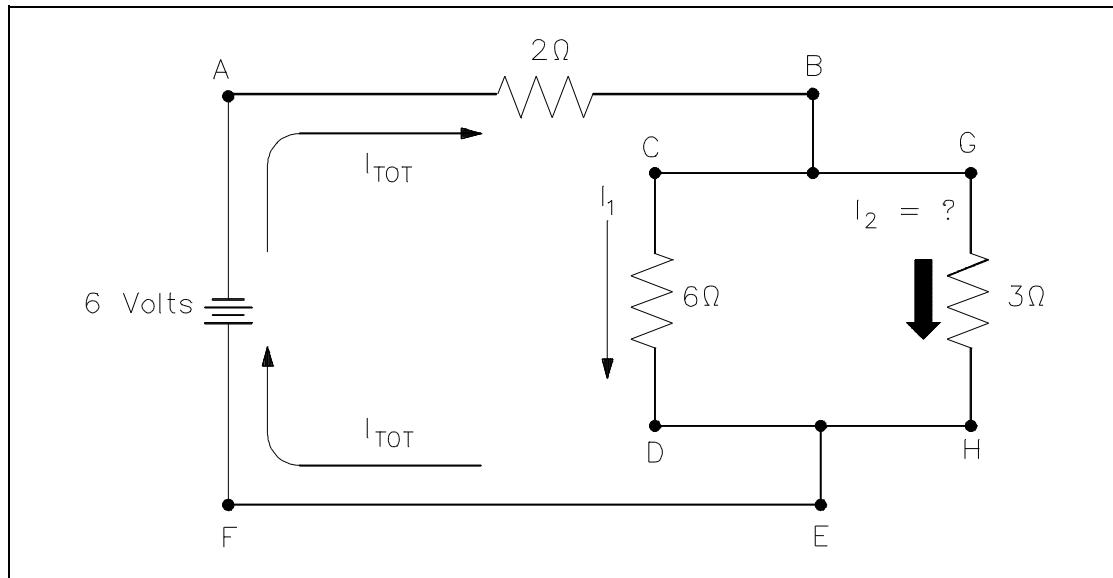


Figure 36 Using the Current Law

Solution:

First, apply Kirchhoff's voltage law to both loops.

Loop ABCDEF

$$\begin{aligned}\sum IR &= \sum E_{\text{source}} \\ 2 I_{\text{total}} + 6 I_1 &= 6\end{aligned}$$

Loop ABGHEF

$$\begin{aligned}\sum IR &= \sum E_{\text{source}} \\ 2 I_{\text{total}} + 3 I_2 &= 6\end{aligned}$$

Since Kirchhoff's current law states $I_{\text{total}} = I_1 + I_2$, substitute $(I_1 + I_2)$ in the place of I_{total} in both loop equations and simplify.

Loop ABCDEF

$$\begin{aligned}2 (I_1 + I_2) + 6 I_1 &= 6 \\ 2 I_1 + 2 I_2 + 6 I_1 &= 6 \\ 8 I_1 + 2 I_2 &= 6\end{aligned}$$

Loop ABGHEF

$$\begin{aligned}2 (I_1 + I_2) + 3 I_2 &= 6 \\ 2 I_1 + 2 I_2 + 3 I_2 &= 6 \\ 2 I_1 + 5 I_2 &= 6\end{aligned}$$

We now have two equations and two unknowns and must eliminate I_1 to find I_2 . One way is to multiply Loop ABGHEF equation by four, and subtract Loop ABCDEF equation from the result.

Multiply by 4:

$$\begin{aligned}4 (2 I_1 + 5 I_2 &= 6) \\ 8 I_1 + 20 I_2 &= 24\end{aligned}$$

Subtract:

$$\begin{array}{r} 8I_1 + 20I_2 = 24 \\ -(8I_1 + 2I_2 = 6) \\ \hline 18I_2 = 18 \end{array}$$

Now we have an equation with only I_2 , which is the current we are looking for.

$$18I_2 = 18$$

$$I_2 = \frac{18}{18} = 1 \text{ ampere}$$

This circuit could have been solved simply by using Ohm's Law, but we used Kirchhoff's Laws to show the techniques used in solving complex circuits when Ohm's Law cannot be used.

Summary

The important information in this chapter is summarized below.

Kirchhoff's Laws Summary

- Kirchhoff's voltage law states that the sum of the voltage drops around a closed loop is equal to the sum of the voltage sources of that loop.
- Kirchhoff's current law states that the current arriving at any junction point in a circuit is equal to the current leaving that junction.
- Since voltage and current can be related to energy and charge, then Kirchhoff's laws are only restating the laws governing energy and charge conservation.

DC CIRCUIT ANALYSIS

All of the rules governing DC circuits that have been discussed so far can now be applied to analyze complex DC circuits. To apply these rules effectively, loop equations, node equations, and equivalent resistances must be used.

EO 1.15 **Given a simple DC circuit, DETERMINE the equivalent resistance of series and parallel combinations of elements.**

Loop Equations

As we have already learned, Kirchhoff's Laws provide a practical means to solve for unknowns in a circuit. Kirchhoff's current law states that at any junction point in a circuit, the current arriving is equal to the current leaving. In a series circuit the current is the same at all points in that circuit. In parallel circuits, the total current is equal to the sum of the currents in each branch. Kirchhoff's voltage law states that the sum of all potential differences in a closed loop equals zero.

Using Kirchhoff's laws, it is possible to take a circuit with two loops and several power sources (Figure 37) and determine loop equations, solve loop currents, and solve individual element currents.

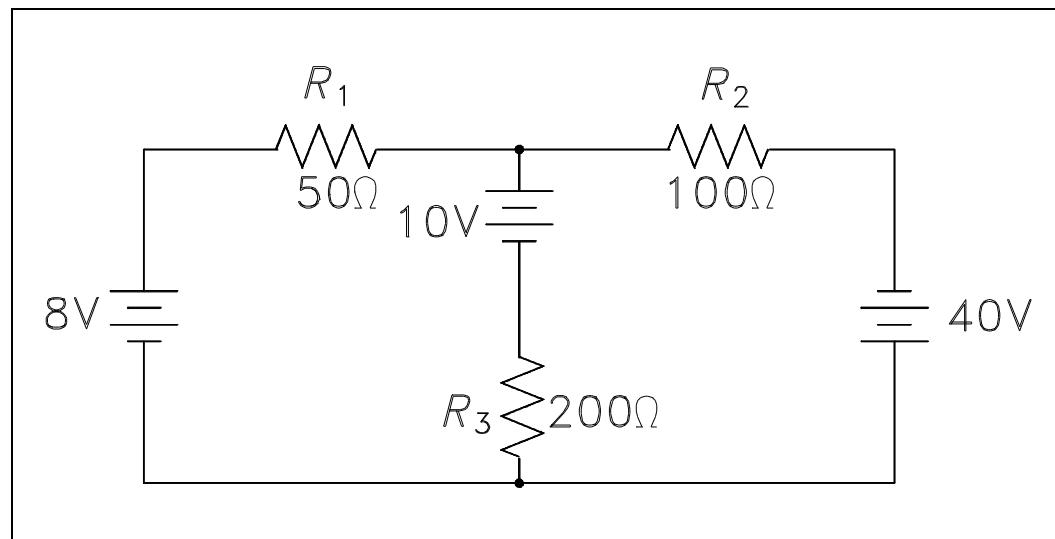


Figure 37 Example Circuit for Loop Equations

The first step is to draw an assumed direction of current flow (Figure 38). It does not matter whether the direction is correct. If it is wrong, the resulting value for current will be negative.

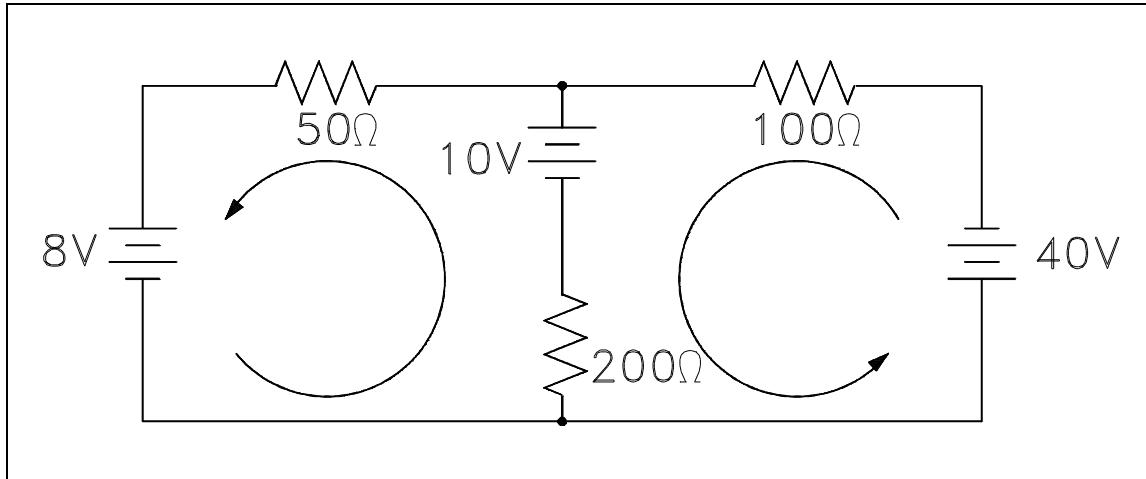


Figure 38 Assumed Direction of Current Flow

Second, mark the polarity of voltage across each component (Figure 39). It is necessary to choose a direction for current through the center leg, but it is not necessary to put in a new variable. It is simply $I_2 - I_1$.

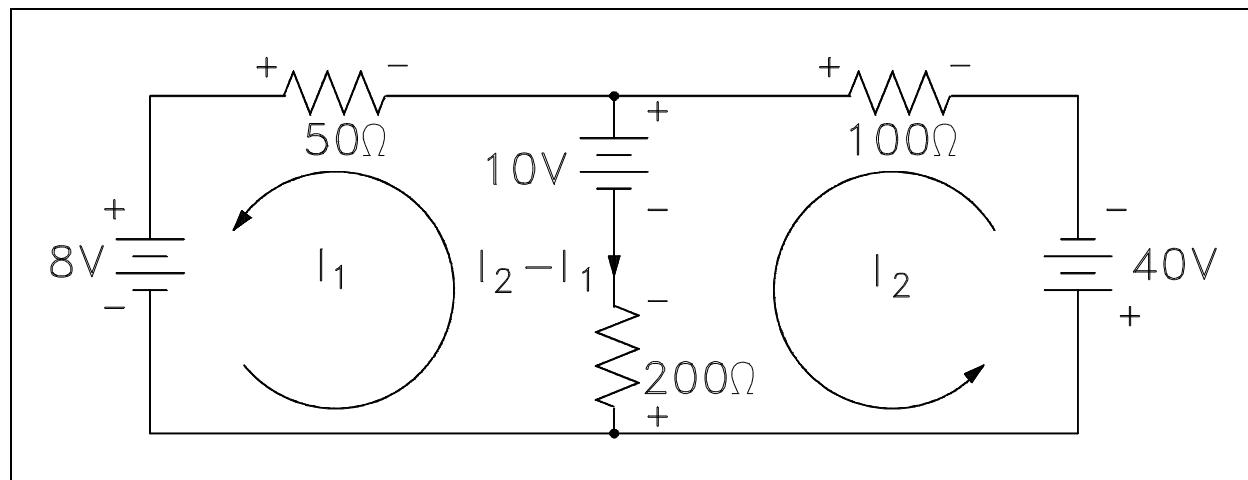


Figure 39 Marking Polarity

Third, apply Kirchhoff's voltage law to loops one and two by picking a point in each loop and writing a loop equation of the voltage drops around the loop; then set the equation equal to zero.

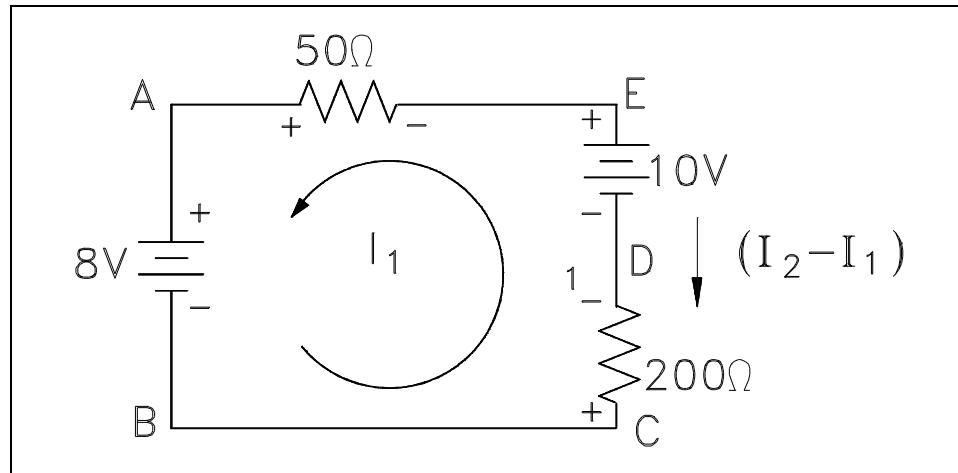


Figure 40 Applying Voltage Law to Loop 1

Figure 40 shows Loop one.

From Point A to Point B, there is an increase in voltage of 8 volts. From Point C to Point D, there is an increase in voltage of 200 ($I_2 - I_1$). From Point D to Point E, there is a decrease in voltage of 10 volts. From Point E to Point A, there is a voltage decrease of $50I_1$ volts. The result in equation form is illustrated in equation (2-16).

$$8 + 200 (I_2 - I_1) - 50 I_1 - 10 = 0 \quad (2-17)$$

Using the same procedure for Loop 2 of Figure 39, the resulting equation is shown in equation (2-18).

$$10 - 200 (I_2 - I_1) + 40 - 100 I_2 = 0 \quad (2-18)$$

Fourth, solve equations (2-17) and (2-18) simultaneously. First, rearrange and combine like terms in the equation for Loop 1.

$$\begin{aligned} -50 I_1 + 200 I_2 - 200 I_1 &= 10 - 8 \\ -250 I_1 + 200 I_2 &= 2 \end{aligned}$$

Divide both sides by two.

$$-125 I_1 + 100 I_2 = 1$$

Rearrange and combine like terms in the Loop 2 equation.

$$\begin{aligned}-200 I_2 + 200 I_1 - 100 I_2 &= -10 - 40 \\ 200 I_1 - 300 I_2 &= -50\end{aligned}$$

Multiplying the Loop 1 equation by 3, and add it to the Loop 2 equation.

$$\begin{aligned}3(-125 I_1 + 100 I_2 = 1) &= -375 I_1 + 300 I_2 = 3 \\ &\quad + 200 I_1 - 300 I_2 = -50 \\ \hline -175 I_1 &= -47\end{aligned}$$

Solving for I_1 :

$$\begin{aligned}-175 I_1 &= -47 \\ I_1 &= \frac{-47}{-175} = 0.2686 \text{ amp} = 268.6 \text{ mA}\end{aligned}$$

Solving for I_2 using the Loop 1 equation:

$$\begin{aligned}-125 (0.2686) + 100 I_2 &= 1 \\ 100 I_2 &= 1 + 33.58 \\ I_2 &= \frac{34.58}{100} \\ I_2 &= 0.3458 \text{ amp} = 345.8 \text{ mA}\end{aligned}$$

The current flow through R_1 (50Ω) is I_1 . The current flow through $R_2(100\Omega)$ is I_2 , and through $R_3(200\Omega)$ is $I_2 - I_1$:

$$I_3 = I_2 - I_1 = 345.8 \text{ mA} - 268.6 \text{ mA}$$

$$I_3 = I_2 - I_1 = 77.2 \text{ mA}$$

Fifth, apply Ohm's Law to obtain the voltage drops across Resistors R_1 , R_2 , and R_3 :

$$V_1 = I_1 R_1 = (0.2686 \text{ amps})(50\Omega) = 13.43 \text{ Volts}$$

$$V_2 = I_2 R_2 = (0.3458 \text{ amps})(100\Omega) = 34.58 \text{ Volts}$$

$$V_3 = (I_2 - I_1) R_3 = (0.0772 \text{ amps})(200\Omega) = 15.44 \text{ Volts}$$

Sixth, check the calculations by applying Kirchhoff's Laws:

Check 1: Apply Kirchhoff's voltage law to the larger outer loop (Figure 41).

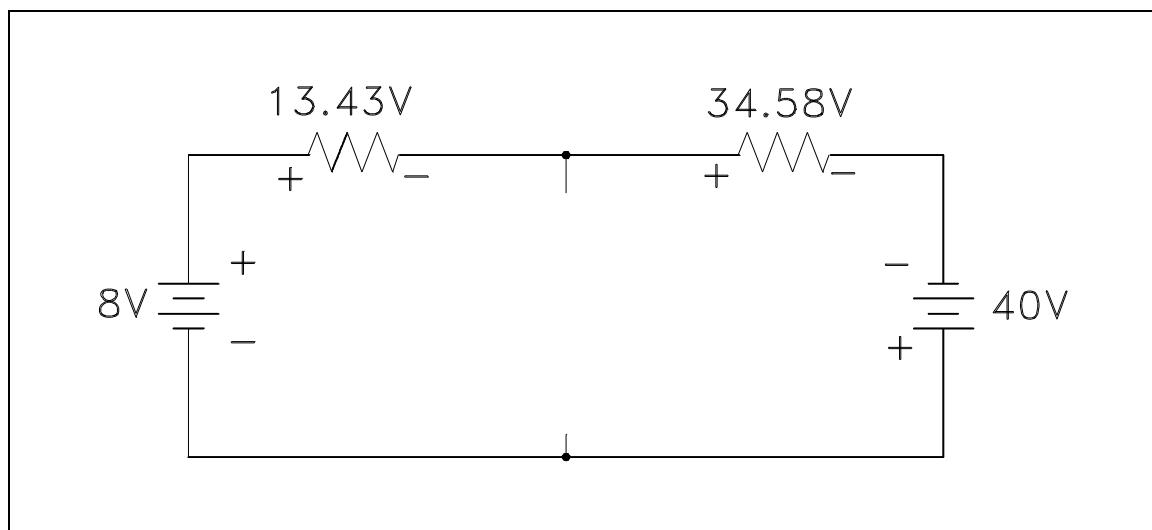


Figure 41 Applying Voltage Laws to Outer Loop

The sum of the voltage drops around the loop is essentially zero. (Not exactly zero due to rounding off.)

$$8 - 13.43 - 34.58 + 40 = 0 \\ -0.01 \cong 0$$

Therefore, the solution checks.

Check 2: Use Kirchhoff's current law at one of the junctions (Figure 42).

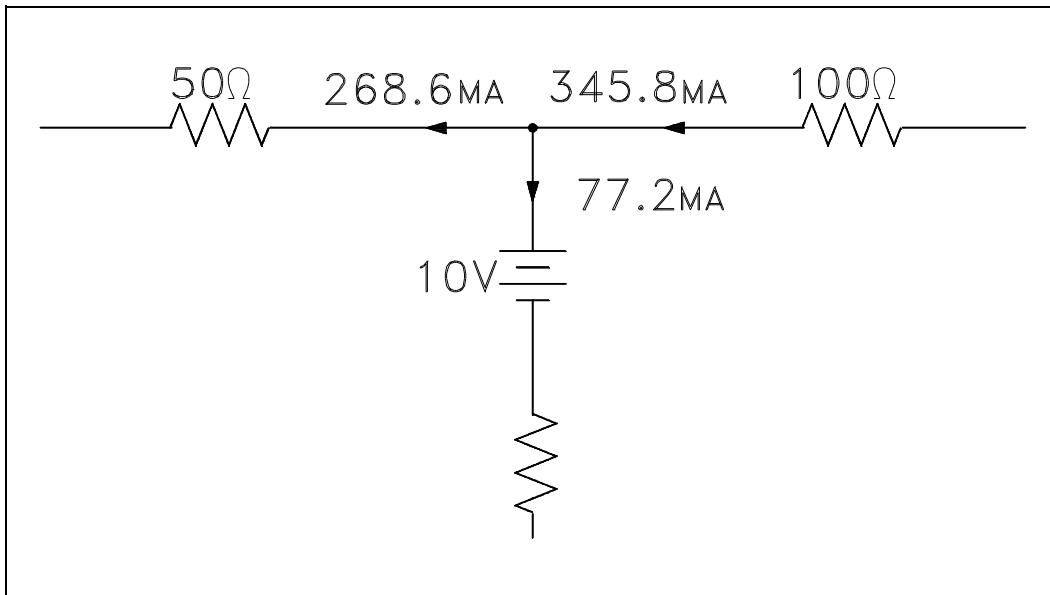


Figure 42 Applying Current Law to Junction

The sum of the currents out of the junction is:

$$\begin{aligned}
 0.2686 + 0.0772 &= 0.3458 \text{ a} \\
 &= 345.8 \text{ ma}
 \end{aligned}$$

The current into the junction is 345.8 ma.

The current into the junction is equal to the current out of the junction. Therefore, the solution checks.

Node Equations

Kirchhoff's current law, as previously stated, says that at any junction point in a circuit the current arriving is equal to the current leaving. Let us consider five currents entering and leaving a junction shown as P (Figure 43). This junction is also considered a node.

Assume that all currents entering the node are positive, and all currents that leave the node are negative. Therefore, I_1 , I_3 , and I_4 are positive, and I_2 and I_5 are negative. Kirchhoff's Law also states that the sum of all the currents meeting at the node is zero. For Figure 43, Equation (2-19) represents this law mathematically.

$$I_1 + I_2 + I_3 + I_4 + I_5 = 0 \quad (2-19)$$

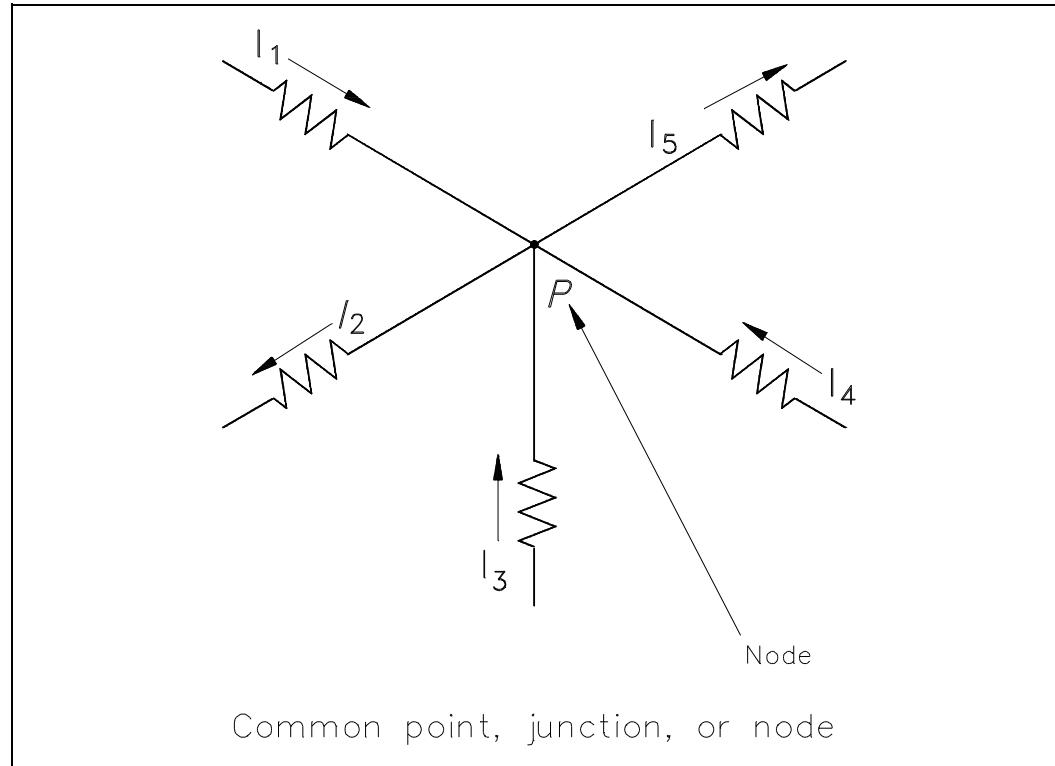


Figure 43 Node Point

By solving node equations, we can calculate the unknown node voltages. To each node in a circuit we will assign a letter or number. In Figure 44, A, B, C, and N are nodes, and N and C are principal nodes. Principal nodes are those nodes with three or more connections. Node C will be our selected reference node. V_{AC} is the voltage between Nodes A and C; V_{BC} is the voltage between Nodes B and C; and V_{NC} is the voltage between Nodes N and C. We have already determined that all node voltages have a reference node; therefore, we can substitute V_A for V_{AC} , V_B for V_{BC} , and V_N for V_{NC} .

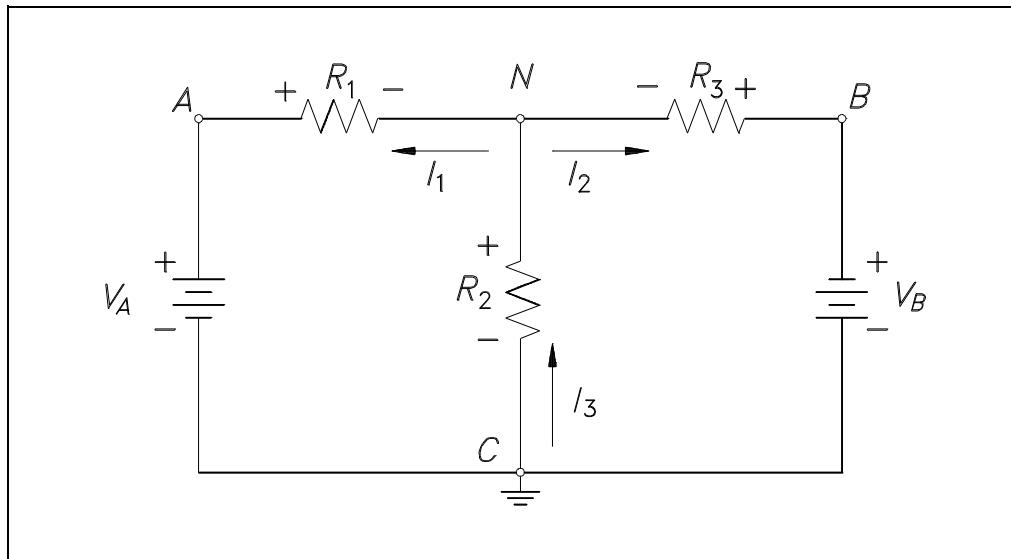


Figure 44 Circuit for Node Analysis

Assume that loop currents I_1 and I_2 leave Node N, and that I_3 enters Node N (Figure 44).

From Kirchhoff's current law:

$$\begin{aligned} \sum I &= 0 \\ I_1 + I_2 + I_3 &= 0 \\ I_3 &= I_1 + I_2 \end{aligned} \tag{2-20}$$

Using Ohm's Law and solving for the current through each resistor we obtain the following.

$$I = \frac{V_R}{R} \text{ where } V_R \text{ is the voltage across resistor, } R.$$

$$I_3 = \frac{V_N}{R_2}$$

$$I_1 = \frac{V_A - V_N}{R_1}$$

$$I_2 = \frac{V_B - V_N}{R_3}$$

Substitute these equations for I_1 , I_2 , and I_3 into Kirchhoff's current equation (2-20) yields the following.

$$\frac{V_N}{R_2} = \frac{V_A - V_N}{R_1} + \frac{V_B - V_N}{R_3}$$

The circuit shown in Figure 45 can be solved for voltages and currents by using the node-voltage analysis.

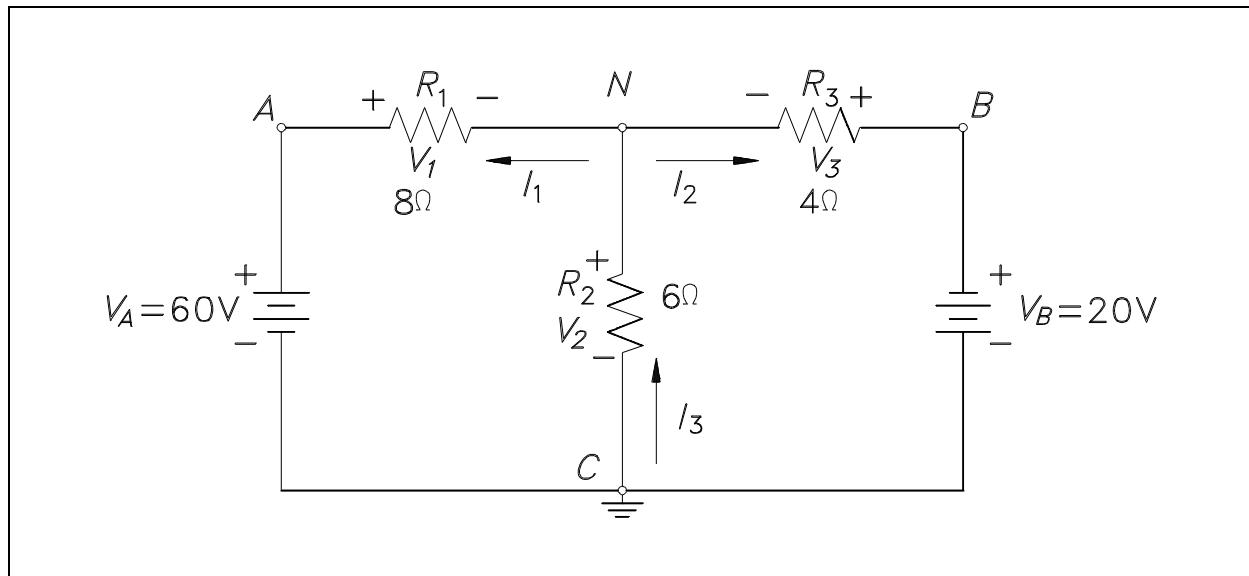


Figure 45 Node - Voltage Analysis

First, assume direction of current flow shown. Mark nodes A, B, C, and N, and mark the polarity across each resistor.

Second, using Kirchhoff's current law at Node N, solve for V_N .

$$\begin{aligned} I_3 &= I_1 + I_2 \\ \frac{V_N}{R_2} &= \frac{V_A - V_N}{R_1} + \frac{V_B - V_N}{R_3} \\ \frac{V_N}{6} &= \frac{60 - V_N}{8} + \frac{20 - V_N}{4} \end{aligned}$$

Clear the fraction so that we have a common denominator:

$$4V_N = 3(60 - V_N) + 6(20 - V_N)$$

$$4V_N = 180 - 3V_N + 120 - 6V_N$$

$$13V_N = 300$$

$$V_N = 23.077$$

Third, find all voltage drops and currents.

$$V_1 = V_A - V_N = 60 - 23.077 = 36.923 \text{ Volts}$$

$$V_2 = V_N = 23.077 \text{ Volts}$$

$$V_3 = V_B - V_N = 20 - 23.077 = -3.077 \text{ Volts}$$

The negative value for V_3 shows that the current flow through R_3 is opposite that which was assumed and that the polarity across R_3 is reversed.

$$I_1 = \frac{V_1}{R_1} = \frac{36.923 \text{ V}}{8\Omega} = 4.65 \text{ amps}$$

$$I_2 = \frac{V_3}{R_3} = \frac{-3.077 \text{ V}}{4\Omega} = -0.769 \text{ amps}$$

$$I_3 = \frac{V_2}{R_2} = \frac{23.077 \text{ V}}{6\Omega} = 3.846 \text{ amps}$$

The negative value for I_3 shows that the current flow through R_3 is opposite that which was assumed.

Series-Parallel Circuit Analysis

When solving for voltage, current, and resistance in a series-parallel circuit, follow the rules which apply to the series part of the circuit, and follow the rules which apply to the parallel part of the circuit. Solving these circuits can be simplified by reducing the circuit to a single equivalent resistance circuit, and redrawing the circuit in simplified form. The circuit is then called an equivalent circuit (Figure 46).

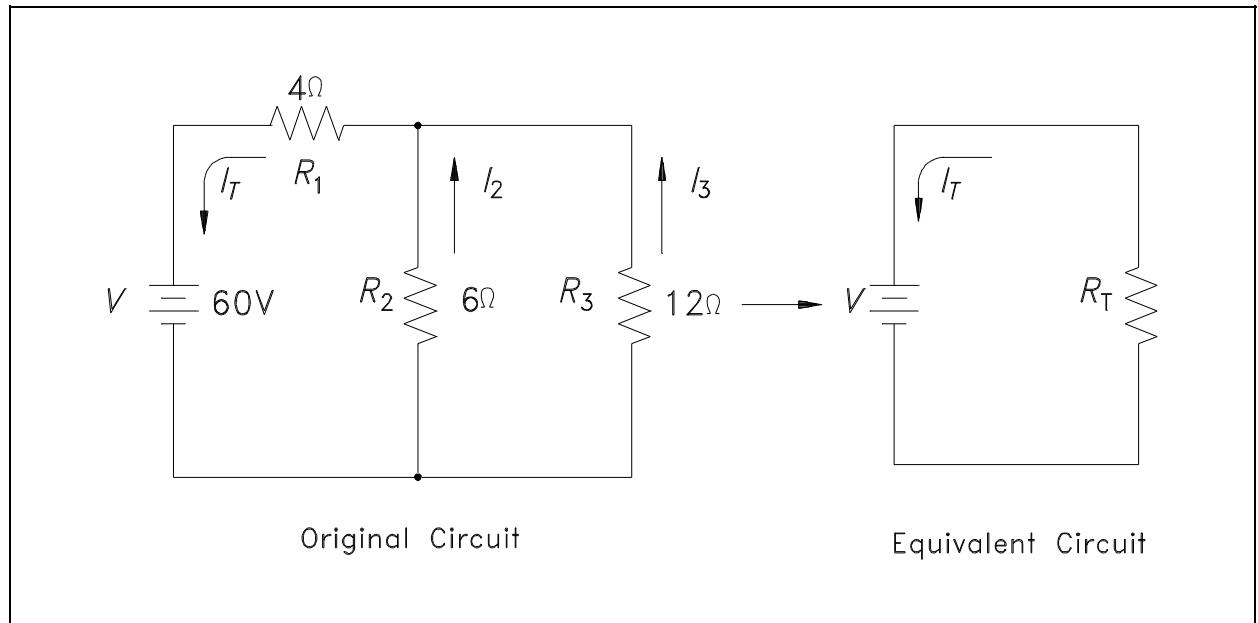


Figure 46 Redrawn Circuit Example

The easiest way to solve these types of circuits is to do it in steps.

Step 1: Find the equivalent resistance of the parallel branch:

$$R_p = \frac{R_2 R_3}{R_2 + R_3} = \frac{(6)(12)}{6 + 12} = \frac{72}{18} = 4\Omega$$

Step 2: Find the resistance of the equivalent series circuit:

$$R_T = R_1 + R_p = 4\Omega + 4\Omega = 8\Omega$$

Step 3: Find total current (I_T):

$$I_T = \frac{V}{R_T} = \frac{60 \text{ V}}{8\Omega} = 7.5 \text{ amps}$$

Step 4: Find I_2 and I_3 . The voltage across R_1 and R_2 is equal to the applied voltage (V), minus the voltage drop across R_1 .

$$V_2 = V_3 = V - I_T R_1 = 60 - (7.5 \times 4) = 30 \text{ V}$$

Then, I_2 and I_3 are calculated.

$$I_2 = \frac{V_2}{R_2} = \frac{30}{6} = 5 \text{ amps}$$

$$I_3 = \frac{V_3}{R_3} = \frac{30}{12} = 2.5 \text{ amps}$$

Y and Delta Network Calculation

Because of its shape, the network shown in Figure 47 is called a T (tee) or Y (wye) network. These are different names for the same network.

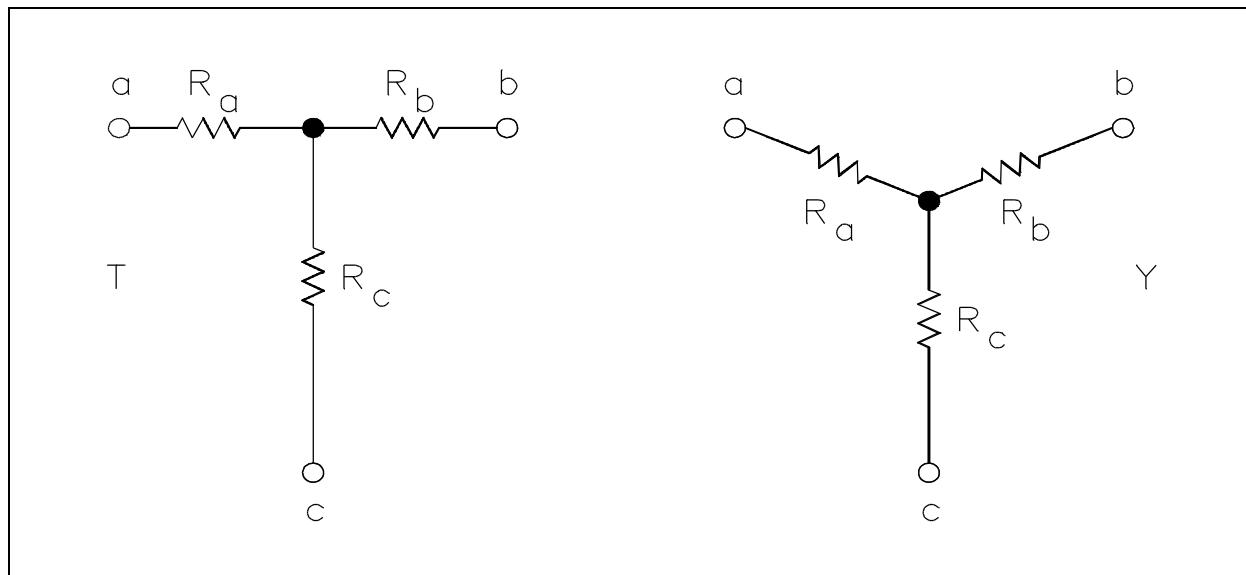


Figure 47 T or Y Network

The network shown in Figure 48 is called π (pi) or Δ (delta) because the shapes resemble Greek letters π and Ω . These are different names for the same network.

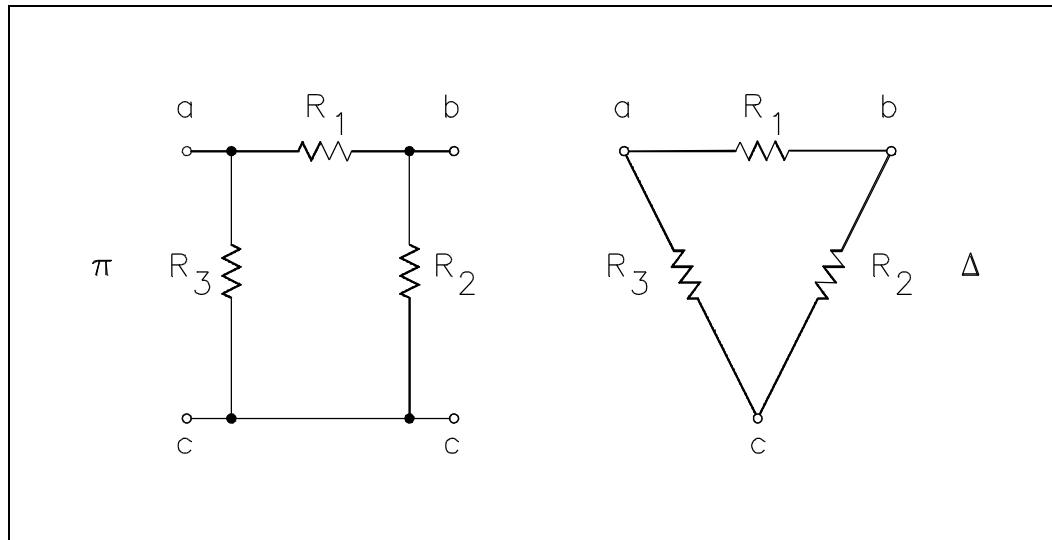


Figure 48 π (pi) or Δ (delta) Network

In order to analyze the circuits, it may be helpful to convert Y to Δ , or Δ to Y , to simplify the solution. The formulas that will be used for these conversions are derived from Kirchhoff's laws. The resistances in these networks are shown in a three-terminal network. After we use the conversion formulas, one network is equivalent to the other because they have equivalent resistances across any one pair of terminals (Figure 49).

Δ to Y conversion:

$$R_a = \frac{R_1 R_3}{R_1 + R_2 + R_3}$$

$$R_b = \frac{R_1 R_2}{R_1 + R_2 + R_3}$$

$$R_c = \frac{R_2 R_3}{R_1 + R_2 + R_3}$$

Rule 1: The resistance of any branch of a Y network is equal to the product of the two adjacent sides of a Δ network, divided by the sum of the three Δ resistances.

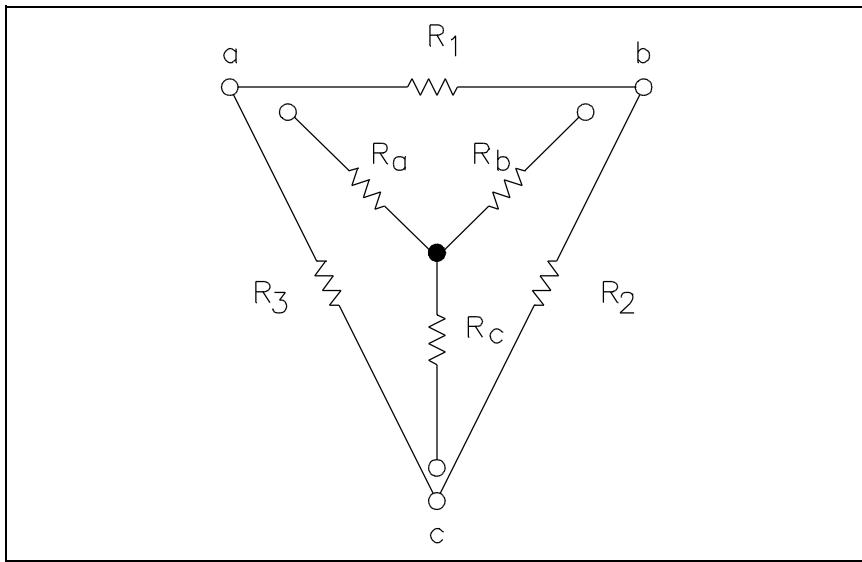


Figure 49 Y - Δ Equivalent

Y to Δ conversion:

$$R_1 = \frac{R_a R_b + R_b R_c + R_c R_a}{R_c}$$

$$R_2 = \frac{R_a R_b + R_b R_c + R_c R_a}{R_a}$$

$$R_3 = \frac{R_a R_b + R_b R_c + R_c R_a}{R_b}$$

Rule 2: The resistance of any side of a Δ network is equal to the sum of the Y network resistance, multiplied in pairs, divided by the opposite branch of the Y network.

Let us consider a bridge circuit (Figure 50).

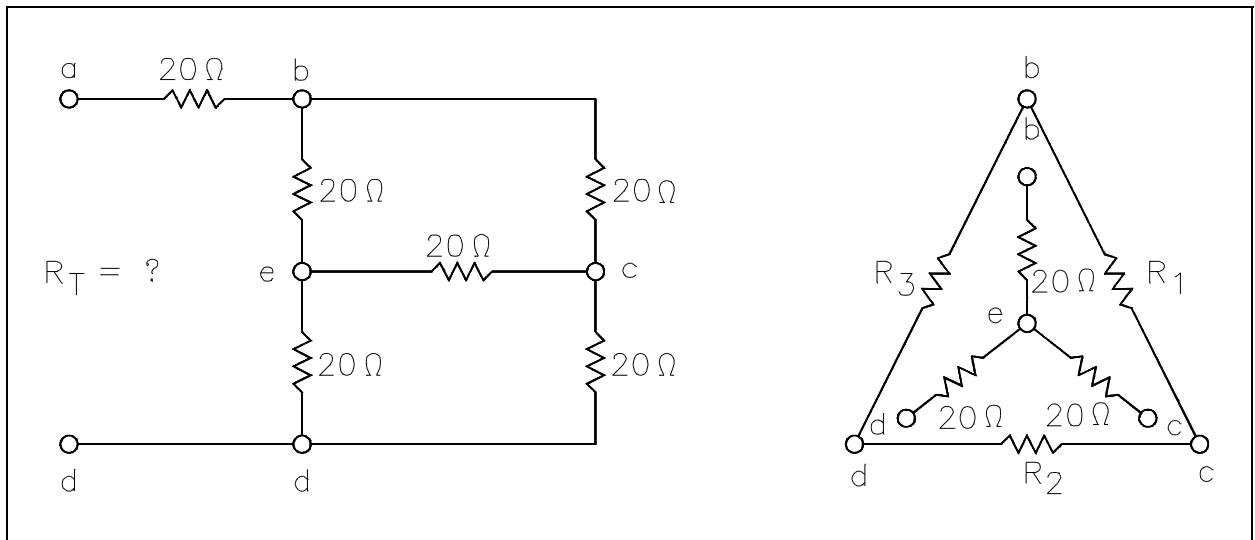


Figure 50 Bridge Circuit

Find R_t at terminals a and d.

Step 1: Convert the Y network (b-e, e-c, e-d) to the equivalent Δ network.

Using Rule 2:

$$R_1 = \frac{(20)(20) + (20)(20) + (20)(20)}{20} = \frac{1200}{20} = 60\Omega$$

$$R_2 = \frac{1200}{20} = 60\Omega$$

$$R_3 = \frac{1200}{20} = 60\Omega$$

Step 2: Now, we can redraw the Y circuit as a Δ circuit and reconnect it to the original circuit (Figure 51):

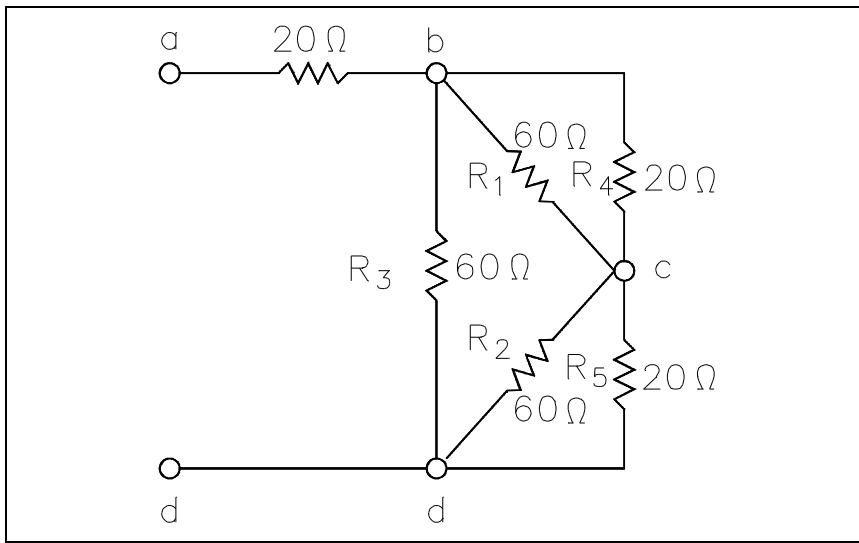


Figure 51 Y - Δ Redrawn Circuit

Step 3: Reduce and simplify the circuit. Note that the 20Ω and 60Ω branches are in parallel in Figure 51. Refer to Figures 51 and 52 for redrawing the circuit in each step below.

$$R_p = \frac{R_1 R_4}{R_1 + R_4} = \frac{(20)(60)}{20 + 60} = \frac{1200}{80} = 15\Omega$$

$$R_q = \frac{R_1 R_5}{R_1 + R_5} = \frac{(20)(60)}{20 + 60} = \frac{1200}{80} = 15\Omega$$

$$R_r = \frac{R_3(R_p + R_q)}{R_3 + (R_p + R_q)} = \frac{(60)(15+15)}{60 + 30} = \frac{1800}{90} = 20\Omega$$

$$R_T = 20 + 20 = 40\Omega$$

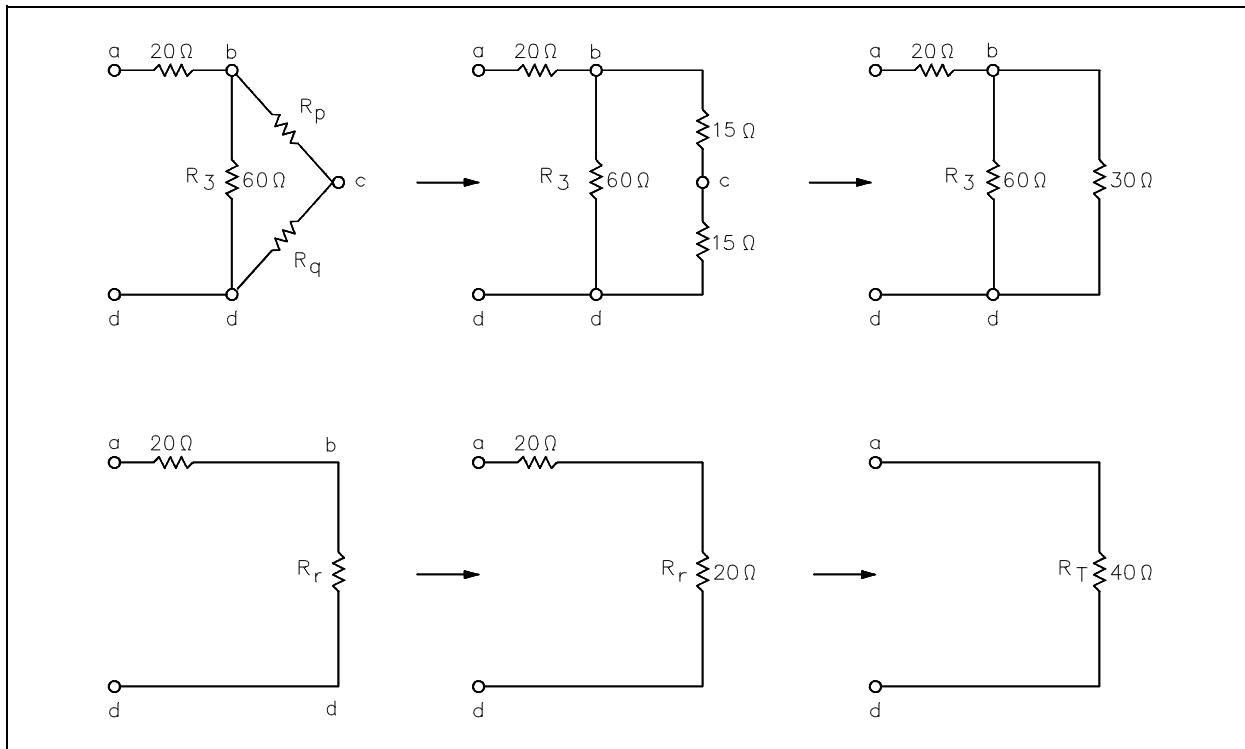


Figure 52 Steps to Simplify Redrawn Circuit

Summary

The important information in this chapter is summarized below.

DC Circuit Analysis Summary

- The current flow at any element in a DC circuit can be determined using loop equations.
- The voltage at any point in a DC circuit can be determined using node equations.
- The equivalent resistance of series and parallel combinations of elements can be used to simplify DC circuit analysis.

DC CIRCUIT FAULTS

Faults within a DC circuit will cause various effects, depending upon the nature of the fault. An understanding of the effects of these faults is necessary to fully understand DC circuit operation.

EO 1.16 DESCRIBE the voltage and current effects of an open in a DC circuit.

EO 1.17 DESCRIBE the voltage and current effects in a shorted DC circuit.

Open Circuit (Series)

A circuit must have a "complete" path for current flow, that is, from the negative side to the positive side of a power source. A series circuit has only one path for current to flow. If this path is broken, no current flows, and the circuit becomes an open circuit (Figure 53).

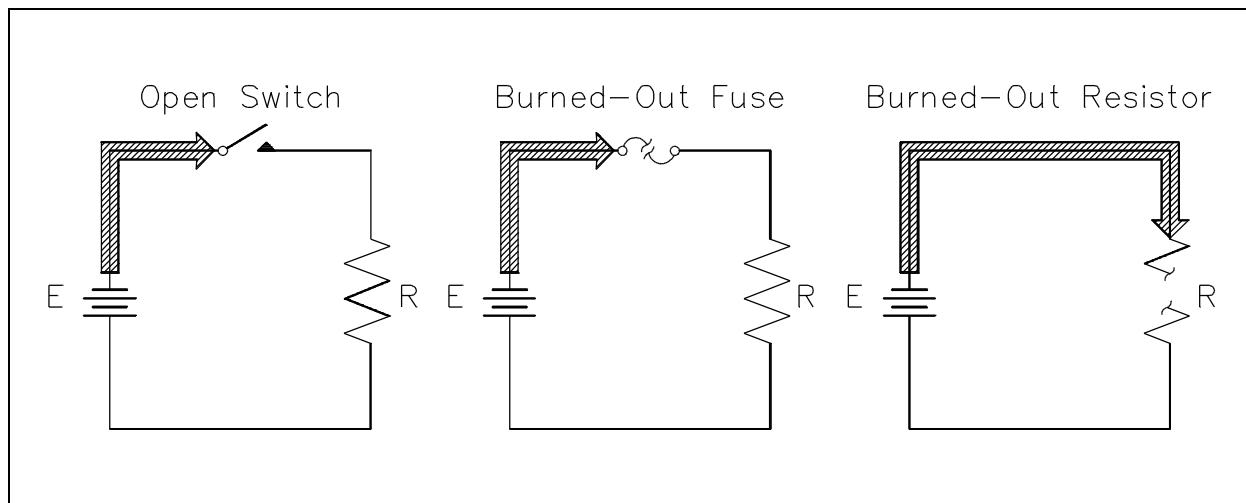


Figure 53 Open Series Circuit

Circuits can be opened deliberately, such as by the use of a switch, or they may be opened by a defect, such as a broken wire or a burned-out resistor.

Since no current flows in an open series circuit, there are no voltage drops across the loads. No power is consumed by the loads, and total power consumed by the circuit is zero.

Open Circuit (Parallel)

A parallel circuit has more than one path for current to flow. If one of the paths is opened, current will continue to flow as long as a complete path is provided by one or more of the remaining paths. It does not mean that you cannot stop current flow through a parallel circuit by opening it at one point; it means that the behavior of a parallel circuit depends on where the opening occurs (Figure 54).

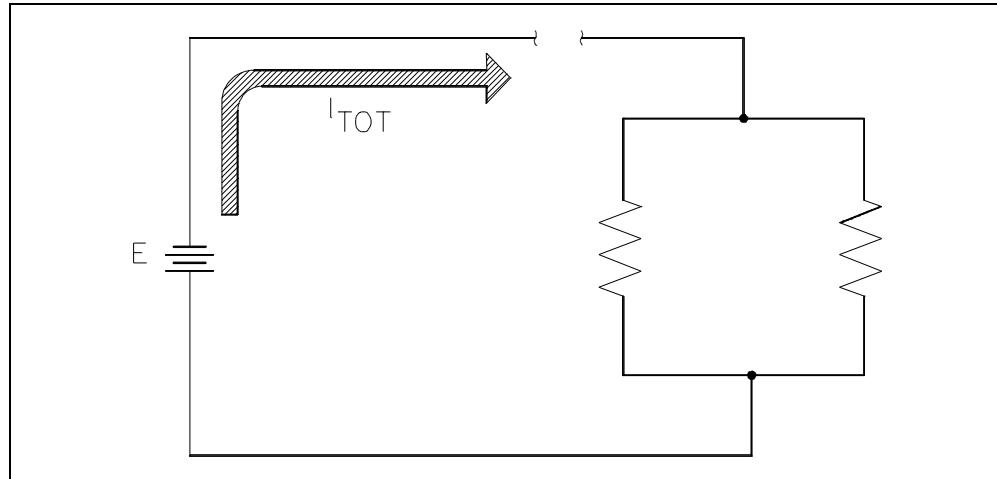


Figure 54 Open Parallel Circuit - Total

If a parallel circuit is opened at a point where only a branch current flows, then only that branch is open, and current continues to flow in the rest of the circuit (Figure 55).

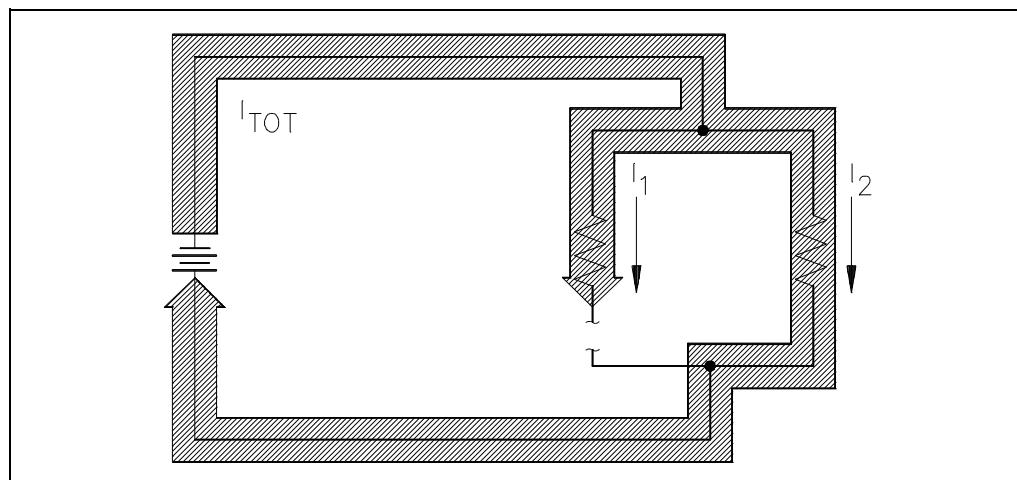


Figure 55 Open Parallel Circuit - Branch

Short Circuit (Series)

In a DC circuit, the only current limit is the circuit resistance. If there is no resistance in a circuit, or if the resistance suddenly becomes zero, a very large current will flow. This condition of very low resistance and high current flow is known as a "short circuit" (Figure 56).

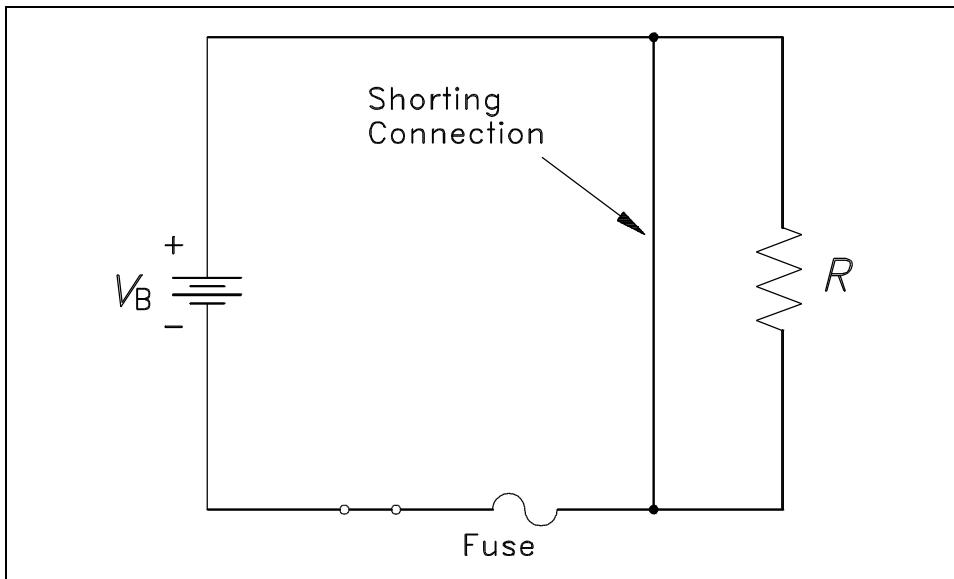


Figure 56 Shorted DC Circuit

A short circuit is said to exist if the circuit resistance is so low that current increases to a point where damage can occur to circuit components. With an increase in circuit current flow, the terminal voltage of the energy source will decrease. This occurs due to the internal resistance of the energy source causing an increased voltage drop within the energy source. The increased current flow resulting from a short circuit can damage power sources, burn insulation, and start fires. Fuses are provided in circuits to protect against short circuits.

Short Circuit (Parallel)

When a parallel circuit becomes short circuited, the same effect occurs as in a series circuit: there is a sudden and very large increase in circuit current (Figure 57).

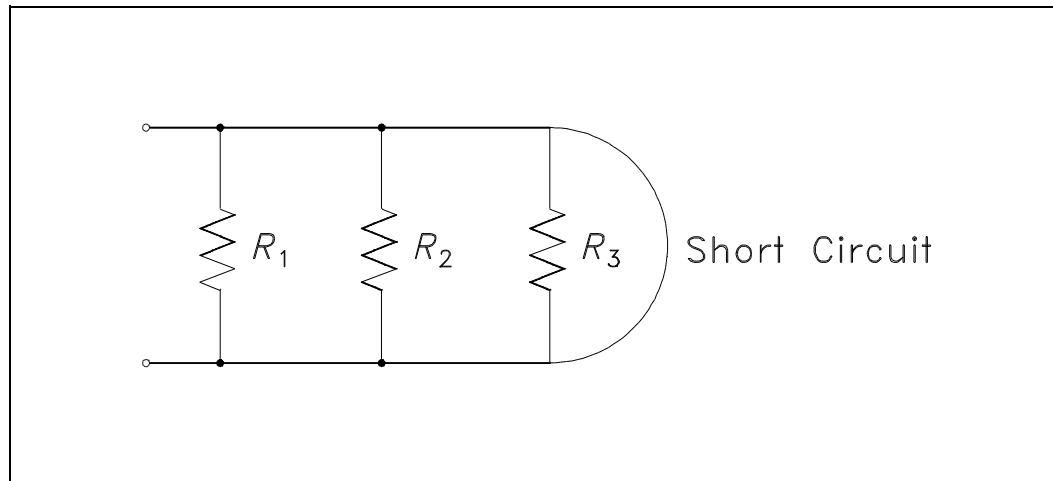


Figure 57 Shorted Parallel Circuit

Parallel circuits are more likely than series circuits to develop damaging short circuits. This is because each load is connected directly across the power source. If any of the load becomes shorted, the resistance between the power source terminals is practically zero. If a series load becomes shorted, the resistance of the other loads keeps the circuit resistance from dropping to zero.

Summary

The important information in this chapter is summarized below.

DC Circuit Faults Summary

- An open series DC circuit will result in no power being consumed by any of the loads.
- The effect of an open in a parallel circuit is dependent upon the location of the open.
- A shorted DC circuit will result in a sudden and very large increase in circuit current.

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